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DOCTORAL THESIS

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Supervisor: Associate Professor Tomislav Capuder, PhD

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Sveučilište u Zagrebu

FAKULTET ELEKTROTEHNIKE I RAČUNARSTVA

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NADOGRADNJA MODELA OPTIMALNIH TOKOVA SNAGA S OGRANIČENJIMA HARMONIČKOGA IZOBLIČENJA I NAPONSKE NESIMETRIJE ZA PLANIRANJE I VOĐENJE DISTRIBUCIJSKIH MREŽA

DOKTORSKI RAD

Mentor: izv. prof. dr. sc. Tomislav Capuder

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Supervisor: Associate Professor Tomislav Capuder, PhD

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About the Supervisor

Tomislav Capuder was born in 1983 in Zagreb. He received his bachelor's and doctoral degrees from the Faculty of Electrical Engineering and Computing, University of Zagreb. At the same Faculty, he was elected as the assistant professor in 2016 and in 2020 as the associate professor. During his doctoral and postdoctoral studies, he spent several months as a visiting researcher at the University of Manchester in the UK. He won the Silver Josip Lončar Award for the best doctoral dissertation at the Faculty of Electrical Engineering and Computing in 2013/2014, the Science Award of the Faculty of Electrical Engineering and Computing for 2015, the Vera Johanides Award of the Croatian Academy of Engineering and many others.

His area of interest covers integrated energy infrastructure, multi-energy systems, electric power systems planning and operation, energy markets, and modelling and optimization of electric power systems, with an emphasis on advanced distribution networks.

He is the author of a chapter in a book, 3 editorial books, more than 50 papers in category A journals, more than 80 papers in conference proceedings with international peer-review, and over 100 technical studies. He is an Editorial Board member in several international scientific and technical journals (International Transactions on Electrical Energy Systems is indexed in the Current Content database). In 2016, he received the award for the best reviewer of the IEEE Transactions on Smart Grid and the award for the best reviewer of the International Journal on Electrical Power and Energy Systems (both journals are indexed in the Current Content database), while in 2019 he received the award for the best reviewer of the IEEE Transactions on Smart Grid and IEEE Transactions on Power Systems.

He is the coordinator of several international and national research and development projects.

He was the secretary of the international conferences Smart Grid World Forum 2010 and European Energy Market 2011, as well as the chairman of the board of the international conference IEEE EUROCON 2013. He was also one of the presidents of the program committee of the international conference IEEE ENERGYCON 2014 and one of the program committee members of IEEE ENERGYCON 2016 and IEEE Energycon 2018. He was the president of the international conference Medpower 2018.

He is a member of scientific and technical associations HRO CIGRE, SDEWES, IEEE, and he serves as a president of the Power & Energy Chapter in the Croatian IEEE section.

He speaks excellent English and speaks German at an intermediate level.

He is married and the father of three children.

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O mentoru

Tomislav Capuder rođen 1983. godine u Zagrebu. Diplomirao je i doktorirao na Fakultetu elektrotehnike i računarstva Sveučilišta u Zagrebu. Na istom Fakultetu izabran je u znanstveno-nastavno zvanje docent 2016. godine, a 2020. Godine u znanstveno-nastavno zvanje izvanredni profesor. Tijekom doktorskog i poslijedoktorskog studija proveo je više mjeseci na usavršavanju na Sveučilištu u Manchesteru u Velikoj Britaniji. Dobitnik je nagrade Srebrni Josip Lončar za najbolju doktorsku disertaciju Fakulteta elektrotehnike i računarstva u 2013/2014 godini, Nagrade za znanost Fakulteta elektrotehnike i računarstva za 2015 godinu, Nagrade Vera Johanides Hrvatske akademije tehnilkih znanosti te mnogih drugih.

Istraživački interesi obuhvaćaju integrirane energetske infrastrukture, višegeneracijske sustave, planiranje i vođenje elektroenergetskih sustava, tržišta energije, modeliranje i optimiranje elektroenergetskog sustava, s naglaskom na napredne distribucijske mreže.

Autor je poglavlja u knjizi, 3 uredničke knjige, više od 50 radova u časopisima kategorije A i više od 80 radova u zbornicima skupova s međunarodnom recenzijom, te preko 100 stručnih studija i elaborata. Član je uredničkih odbora nekoliko međunarodnih znanstveno stručnih časopisa (od čega je International Transactions on Electrical Energy Systems indeksira u Current Content bazi). U 2016. godini dobio je nagradu za najboljeg recenzenta časopisa IEEE Transactions on Smart Grid i nagradu za najboljeg recenzenta časopisa International Journal on Electrical Power and Energy Systems (oba časopisa indeksirana su u bazi Current Content), dok je u 2019. godini dobio je nagradu za najboljeg recenzenta časopisa IEEE Transactions on Smart Grid i IEEE Transactions on Power Systems.

Voditelj je više međunarodnih i nacionalni znanstveno-istraživačkih i razvojnih projekata.

Bio je tajnik međunarodnih konferencija Smart Grid World Forum 2010 i European Energy Market 2011 te predsjednik Organizacijskog odbora međunarodne konferencije IEEE EURO-CON 2013. Također bio jedan od predsjednika programskog odbora međunarodne konferencije IEEE ENERGYCON 2014, te je jedan od članova programskog odbora IEEE ENERGYCON 2016 i IEEE Energycon 2018. Bio je predsjednik međunarodne konferencije Medpower 2018.

Član je znanstvenih i stručnih udruga HRO CIGRE, SDEWES, IEEE, a u Hrvatskoj sekciji IEEE trenutno obnaša dužnost Predsjednika Odjela za energetiku.

Izvrsno se služi engleskim jezikom te na srednjoj razini koristi njemačkim jezikom.

Oženjen je i otac troje djece.

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Preface

First of all, I would like to thank my parents for always encouraging me to study and continue my education.

Additional thanks to my Grža, for helping me decide to start writing the thesis and "making" me finish its writing on time.

I would also like to thank everyone who participated in the work and research leading to my PhD degree, especially professor Andrew Keane, who supported me during my stay at University College Dublin, and Frederik Geth, from whom I learned a lot about distribution networks' modelling and optimisation.

Finally, a special thanks goes to my supervisor, professor Tomislav Capuder. I enjoyed all the interaction and our collaboration. Thank you for making it fun.

Abstract

Due to their positive impact on the environment, the decline in their price, and potential financial benefit for end-users in power systems, the share of renewable energy sources and other technologies with a low carbon footprint, including electric vehicles and heat pumps, is continuously growing, especially in distribution networks. Despite the benefits, the integration of distributed energy resources (DERs) is often uncoordinated, focusing only on the financial and environmental aspects and neglecting the potential technical challenges in planning and operating distribution networks. Distribution system operators (DSOs) and other policy-makers are becoming more aware of the potential problems caused by DERs, and prior to their connection to a network, they require detailed techno-economical analyses that will justify their integration but also ensure that the safe and reliable operation of a network will not be endangered.

This thesis identifies three main problems that aggravate the planning and operation of distribution networks: low observability and network data of insufficient correctness, the lack of tools and methods that enable complex and precise analyses of distribution networks, and the unused potential of end-users in contributing to the improvement of distribution network technical conditions.

The low observability of the distribution network is becoming less of a problem due to the installation of smart meters enabling monitoring of a network closer to real-time. Digitisation also enables the visualisation of network elements together with storing their technical attributes in tools and databases that rely on the geographic information system (GIS). Even though GIS data of a distribution network is a prerequisite for creating a mathematical model of a network that enables further analyses, they often contain different errors that prevent their use in the initial form. The thesis gives an overview of different approaches dealing with the lack of distribution network data and their low-observability problems. One of the approaches is creating and using synthetic benchmark distribution network models that are efficient in verifying tools and methods developed for different analyses and simulations. However, these models cannot be used in real-world analyses and for that reason, the focus is put on developing methods that remove the errors in a real-world distribution network GIS data set. No matter if analyses rely on benchmark or real-world networks, it is necessary to create the mathematical representation of a network, which becomes challenging in distribution and especially low voltage (LV) networks. Due to their specific configuration and other characteristics, some models of LV distribution networks can lead to the loss of accuracy but also to the loss of computational efficiency. The thesis presents a developed method for detecting and removing GIS errors in a data set representing real-world LV distribution network elements. Errors were detected based on the analysis of a large data set containing multiple LV networks. The method is automatised, making it easy to use but also to extend with new functionalities needed in the case of newly detected errors.

Due to the already mentioned specific characteristics, tools used and conclusions drawn from traditional power system analyses are not valid in the case of distribution networks. Therefore, there is a need to develop new tools and methods that will be used in distribution network simulations and analyses. The main focus of the thesis is put on two types of analyses - the analysis of power quality (PQ) disturbances and analyses based on optimal power flow (OPF) models. DERs, more precisely, their power electronic interface to a network, and non-linear loads already in a network are identified as the sources of deteriorating the values of voltage magnitude, voltage unbalance factor and total voltage harmonic distortion. The review of different approaches aimed at the PQ indicators improvement presents methods oriented on the often costly and complex utilisation of physical devices and activating the flexibility potential of end-users. Controllable and flexible loads in households, together with the DERs owned by end-users can contribute to mitigating different technical issues in the network. However, end-users are often distracted from providing flexibility services by the potential discomfort the request for changing electricity consumption causes. Therefore, the thesis presents several non-invasive approaches oriented toward maintaining the desired level of comfort during end-users participation in providing flexibility services for PQ improvement.

The exact formulation of OPF models is nonlinear and nonconvex, making the formulation unscalable, intractable, and computationally inefficient. Therefore, there are many approximation approaches for lowering the complexity of the OPF problem. The thesis is oriented on an overview of linearisation, relaxation, and approaches using machine learning algorithms for solving power system equations. However, all of these approaches can lead to the loss of accuracy, so the nonlinear OPF formulations, together with their implementation and potential application, are also presented. The thesis complements the review of OPF formulations with the nonlinear formulation of the three-phase OPF model extended with voltage unbalance and harmonic distortion constraints.

Keywords: distribution networks; distributed energy resources; geographic information system; optimal power flow; power quality

Nadogradnja modela optimalnih tokova snaga s ograničenjima harmoničkoga izobličenja i naponske nesimetrije za planiranje i vođenje distribucijskih mreža

Elektroenergetski sektor značajno doprinosi emisijama CO_2 i ostalih stakleničkih plinova koji dovode do povećanja temperature i ostalih klimatskih promjena. Kako bi se smanjio njegov doprinos, elektroenergetski sektor u zadnjim godinama prolazi kroz brojne promjene uzrokovane zahtjevima za smanjenjem ugljičnog otiska. Na razini sustava, tradicionalni izvori energije kao što su nafta, ugljen i plin zamjenjuju se proizvodnjom iz obnovljivih izvora energije (OIE) što uključuje varijabilne izvore sunce i vjetar, ali i izvore sličnije tradicionalnim, primjerice biomasa ili potencijal vode. Promjene su prvotno bile vidljive u povećanju udjela proizvodnje električne energije iz elektrana koje su pogonjene obnovljivim izvorima energije, a njihov utjecaj je bio značajan za prilike u prijenosnoj mreži. Međutim, brojne inicijative Europske unije i ostalih zemalja, pad cijena OIE i ostalih niskougljičnih tehnologija, npr. električnih vozila i toplinskih pumpi, te poticaji za krajnje korisnike električne energije za ulaganje u OIE i niskougljične tehnologije povećavaju njihov udio i uzrokuju promjene u distribucijskoj mreži. Bez obzira na okolišnu, klimatsku i financijsku korist integracije niskougljičnih tehnologija u distribucijsku mrežu, integracija je često nekoordinirana, bez detaljnog ispitivanja i istraživanja njenog utjecaja na tehničke prilike u distribucijskim mrežama. S obzirom na takav pristup, operator distribucijskog sustava (ODS) se susreće s brojnim izazovima u planiranju i vođenju distribucijskih mreža.

Novonastali izazovi i problemi se mogu riješiti korištenjem alata i modela koji su orijentirani na analize i simulacije distribucijskih mreža. Međutim, distribucijske mreže sadrže određene karakteristike, npr. R/X omjer > 1, radijalna konfiguracija mreže, potreba za promatranjem sve tri faze, itd., koje onemogućuju primjenu alata i modela korištenih u prijenosnim mrežama te dovode do zahtjeva za razvojem novih rješenja koja uspješno svladavaju izazove nastale specifičnostima distribucijskih mreža. Fokus doktorske disertacije stavljen je upravo na pregled takvih modela, ali i na razvoj novih modela, koje može koristiti ODS, ali i ostali donosioci odluka u elektroenergetskom sektoru.

Preduvjet za analize i simulacije distribucijskih mreža su dostupna mjerenja i modeli mreže. Međutim, distribucijske mreže su tradicionalno niskoosmotrive, tj. udio pohranjenih mjerenja i modela mreže nije dovoljno visok. Nedostatak osmotrivosti distribucijske mreže je još jedan od razloga kompleksnosti razvoja metoda i alata za analize distribucijskih mreža. U posljednjih nekoliko godina situacija se mijenja te distribucijske mreže postaju sve više osmotrive. Nekoliko je glavnih razloga tome, ali zasigurno najveći je sve veća dostupnost informacijskih tehnologija koja doprinosi digitalizaciji, glavnom preduvjetu povećanja stupnja osmotrivosti distribucijskih mreža.

Mjerenja o potrošnji električne energije nekada su bila prikupljana isključivo u transformatorskim stanicama koje su povezivale prijenosnu i distribucijsku mrežu. Opterećenja transformatorskih stanica i krajnjih korisnika u ostatku srednjonaponske (SN) i niskonaponske (NN) mreže nisu bila poznata te su računata korištenjem nadomjesnih krivulja opterećenja ili pretpostavkama o raspodjeli ukupnog opterećenja sukladno nazivnoj snazi transformatorske stanice ili priključne snage krajnjeg korisnika. U posljednje vrijeme, transformatorske stanice koje povezuju dvije SN ili SN i NN razinu sve se češće opremaju naprednim mjernim uređajima koji ovisno u vremenskoj rezoluciji prikupljanja podataka pružaju dostupnost mjerenja u gotovo stvarnom vremenu. Također, sve je veći broj krajnjih korisnika u distribucijskim mrežama čija su tradicionalna brojila potrošnje električne energije zamijenjena naprednim brojilima s kojih se potrošnja pohranjuje u većem broju vremenskih trenutaka. Veća dostupnost mjerenja prvi je preduvjet za uspješne analize distribucijskih mreža.

Podatci o elementima distribucijskih mreža kao što su transformatorske stanice, nadzemni vodovi ili podzemni kabeli u prošlosti su bili pohranjeni u nedigitalnom obliku, koristeći papirnati zapis i kartografske prikaze. Razvojem računalne tehnologije omogućeni su digitalni prikaz i pohrana podataka o elementima distribucijske mreže. U svrhu vizualizacije podataka sve češće se koriste geoprostorne baze podataka i alati temeljeni na geografskom informacijskom sustavu (GIS), koji osim prostornog prikaza nude i mogućnost prikaza tehničkih karakteristika elemenata distribucijske mreže. Međutim, GIS podatci i dalje nisu dostupni za sve distribucijske mreže, a njihovo korištenje u izradi modela potrebnih za analize distribucijskih mreža nije uvijek moguće. Iz tog razloga sve je veći broj sintetičkih, referentnih mreža koje se koriste u proračunima elektroenergetskih mreža. Glavna uloga sintetičkih mreža je omogućiti veći broj modela koji se mogu koristiti u verifikaciji razvijenih modela i alata. S obzirom na to da u najvećem broju slučajeva one ne prikazuju stvarne mreže, zaključci doneseni u analizama temeljenima na njihovom korištenju vrijede u slučaju koji ne odražava stvarno stanje. Sintetičke mreže se kreiraju na temelju statističke obrade velikog skupa dostupnih podataka koji sadrže informacije o postojećim stvarnim mrežama sustava koji su okarakterizirani visokom razinom osmotrivosti.

U slučaju korištenja stvarnih distribucijskih mreža u analizama, najčešći pristup temeljen je na GIS podatcima koji se uređuju na odgovarajući način. Međutim GIS podatci često sadrže veliki broj grešaka u svojem početnom obliku, a te greške ih čine neiskoristivim. Kako bi se ipak ostvario puni potencijal GIS podataka, pažnja se pridaje promatranju velikog skupa i broja podataka. U skupu podataka potrebno je detektirati greške koje se pojavljuju i koje je potrebno ukloniti kako bi podatci postali iskoristivi. Detektirani problemi su često vezani uz geoprostorna svojstva podataka, primjerice problemi s povezanosti elemenata u sustavu. Na temelju svih detektiranih grešaka određuje se pristup koji će koristiti prilikom njihovog uklanjanja. Pristup ja najlakše povezati s izborom alata i programa koji su prikladni za rad s geoprostornim podatcima. Dostupni su brojni alati koji su namijenjeni isključivo za rad s GIS podatcima, međutim, njihovom primjenom nije moguće osigurati jedinstveno rješenje s obzirom na to da je svaki skup podataka potrebno zasebno ručno urediti. S druge strane, različiti programski jezici koji zahtijevaju pisanje programskog koda omogućuju automatizirani pristup uklanjanju grešaka. Takav pristup moguće je opetovano primjenjivati za različite mreže, a važna je i mogućnost proširenja funkcionalnosti takvih metoda u slučajevima identifikacije novih karakterističnih grešaka.

Bez obzira koriste li se sintetički podatci ili podatci o stvarnim distribucijskim mrežama, stvaranje matematičkog modela mreže bez njih nije moguće. Pod matematičkim modelom mreže podrazumijeva se stvaranje prikaza mreže koji se koristi u simulacijskim alatima. Iako je u slučaju linijskih ili simetričnih konfiguracija mreža kreiranje modela jednostavno, izazov predstavljaju trofazne mreže i njihove specifičnosti. Podatke o mreži je moguće direktno povezati sa simulacijskim alatima koji onda automatski stvaraju odgovarajući model mreže i u tom slučaju najčešće nema poteškoća. U slučajevima kada se razvijaju posebni alati sa specifičnom primjenom jedan od prvih koraka je kreiranje matematičkog prikaza mreže na temelju dostupnih podataka. Jedan od najčešće korištenih pristupa je metoda simetričnih komponenti, koja na temelju poznatih vrijednosti o impedanciji nultog, direktnog i inverznog sustava stvara matricu dimenzija 3x3 koja sadrži fazne vrijednosti impedancije. Iako jednostavan, taka pristup unosi pretpostavke koje su često netočne i unose grešku u kasnijim proračunima i analizama. S obzirom na to da su trofazne distribucijske mreže često četverožične zbog postojanja nul-vodiča, veliki broj metoda na temelju geometrijskih svojstava vodova i kabela kreira matrice dimenzija 4x4. Iako su takve matrice točnije, one u proračune unose dodatnu dimenziju koja povećava kompleksnost proračuna i čini ih računski neefikasnima. Zbog toga postoje brojne matematičke metode i razni pristupi koji dimenzije matrica smanjuju na 3x3 te uz potencijalan minimalan gubitak točnosti ne uzrokuju dodatnu kompleksnost trofaznih proračuna. Nedostatak takvog pristupa modeliranju mreže je što potrebni podatci često nisu dostupni što otežava kreiranje matematičkog prikaza. Međutim, u zadnje vrijeme počeli su se javljati pristupi koji na temelju poznatih vrijednosti impedancija nultog, direktnog i inverznog sustava kreiraju matricu dimenzija 3x3 koja je točnija od direktne pretvorbe iz sustava simetričnih komponenti u fazni sustav.

Nakon prikupljanja podataka o potrošnji električne energije u sustavu i podataka o elementima mreže te njihovog uređivanja, podatke je moguće iskoristiti za stvaranje modela mreže i povezivanje sa simulacijskim alatima. Poznate činjenice o tehničkim prilikama u pasivnim distribucijskim mrežama kao što su tokovi snaga od pojne transformatorske stanice do mjesta potrošnje i povećanje pada napona s udaljenosti od pojne stanice više ne vrijede rastućim udjelom distribuiranih izvora energije kao što su fotonaponske elektrane, električna vozila, toplinske pumpe i baterijski spremnici. Svaka od spomenutih tehnologija drugačije utječe na prilike u mreži, a već poznate pretpostavke više ne vrijede. Zbog toga je potrebno provesti detaljne analize distribucijskih mreža kako bi se točno procijenio utjecaj distribuiranih izvora energije na tehničke prilike u mreži. Za analize se koriste simulacijski alati koji mogu biti komercijalni ili javno dostupni. U najvećem broju slučajeva moguće je koristiti i jedne i druge alate, a odabir najviše ovisi o navikama i željama korisnika. Komercijalni alati kao što su NEPLAN, Power Factory, ETAP ili PSS/E su intuitivni i njihovo korištenje je jednostavno s obzirom na to da su temeljeni na grafičkom sučelju u kojemu je moguće jednostavno nacrtati elemente distribucijske mreže i definirati vrijednosti njihovih parametara. Također, takvi alati nude veliki broj analiza te je u slučaju njihova korištenja pretpostavljena točnost rezultata koju nije potrebno dodatno ispitivati. S druge strane, komercijalni alati često zahtijevaju skupe licence, teško ili nemoguće ih je povezati s drugim alatima ili bazama podataka te u slučaju potrebe nije ih moguće nadograditi novim funkcionalnostima. Kao rješenje se u zadnje vrijeme javlja sve veći broj javno dostupnih alta kao što su Matpower, pandapower ili OpenDSS. Takvi alati su često bazirani na programima otvorenog koda i omogućuju simulacije distribucijskih mreža uz jednostavno povezivanje s drugim alatima, sustavima i bazama podataka, ali i nadograđivanje funkcionalnosti u slučajevima kada je to potrebno. Nedostatak takvih alata je što često nisu intuitivni, ne temelje se na grafičkom slučaju i za njihovo korištenje i razvoj je potreban dodatan set vještina.

Fotonaponske elektrane dostižu najveće vrijednosti proizvodnje tijekom dana, u vrijeme kada je potrošnja električne energije smanjenja. To posebno vrijedi za potrošnju u NN mrežama, s obzirom na to da je većina korisnika na poslu i ne troši električnu energiju u kućanstvima. Takav scenarij dovodi do lokalne proizvodnje koja je značajno veća od potrošnje, tokova snaga prema pojnoj transformatorskoj stanici i u konačnici do porasta iznosa napona i pojave nadnapona. Jednaki zaključci vrijede i u slučaju priključenja ostalih distribuiranih izvora proizvodnje, ali i baterijskih spremnika koji u određenim slučajevima mogu proizvesti značajan višak električne energije, a sve u svrhu ostvarivanja zadane funkcije cilja. Nadnapon može uzrokovati proradu zaštite, ali i iznose struja koja dovode do zagrijavanja i smanjenja učinkovitosti motora i ostalih uređaja. U slučaju instalacije distribuiranih izvora potrošnje kao što su toplinske pumpe i električna vozila koja nemaju mogućnost upravljivog punjenja, javlja se suprotan efekt, tj. javljaju se vrijednosti napona iznosa koji je niži od dozvoljenog, struje koje teku vodovima su višeg iznosa, a dodatno se povećavaju i gubitci u distribucijskoj mreži. S obzirom na to da kao i pojava nadnapona, pojava preniskih vrijednosti napona negativno utječe na pouzdan i siguran pogon distribucijskog sustava, potrebno je ograničiti iznose napona na vrijednosti unutar granica propisanih normama i Mrežnim pravilima distribucijskog sustava. Metode za uklanjanje naponskih problema u mreži moguće je podijeliti na metode koje se temelje na iskorištavanju uređaja energetske elektronike i ostalih fizičkih uređaja instaliranih u mrežu te na metode koje potiču krajnje korisnike na pružanje usluga fleksibilnosti kojima će promjenom svoje potrošnje i/ili proizvodnje pridonijeti regulaciji napona. Promjenom konfiguracije i načina rada fizičkih uređaja moguće je injektirati ili povući iz mreže jalovu energiju kako bi se postigla regulacija napona jalovom snagom. Također, moguće je ograničiti snagu proizvodnih jedinica i u trenutcima vršne proizvodnje smanjiti njezin iznos u svrhu poboljšanja naponskih prilika. S obzirom na lokalnu karakteristiku napona, promjenom potrošnje krajnjih korisnika i upravljanjem uređaja koji su definirani kao izvori fleksibilnosti moguće je pridonijeti promjeni iznosa napona u promatranom dijelu distribucijske mreže. Također, električna vozila i baterijski spremnici u vlasništvu krajnjih korisnika mogu imati definirano upravljivo punjenje i pražnjenje koje u trenutku primitka signala može uzrokovati promjenu od tradicionalnog obrasca proizvodnje ili potrošnje te tako poboljšati naponske prilike u sustavu.

Većina uređaja krajnjih korisnika u NN mreži je jednofazno priključena što znači da pojedine faze krajnjeg korisnika nije simetrično raspodijeljeno. Ovisno o njihovoj priključnoj snazi, distribuirani izvori energije su priključeni jednofazno ili trofazno. U slučaju jednofaznog priključenja, razlika između faznih opterećenja se povećava što uzrokuje i povećanje naponske nesimetrije u mreži. Naponska nesimetrija je direktno povezana s povećanjem iznosa tehničkih gubitaka u mreži, a uzrokuje i neželjeno zagrijavanje motora, smanjenje efikasnosti i smanjenje životnog vijeka uređaja. Naponska nesimetrija se može ograničiti trofaznim priključenjem svih distribuiranih izvora energije, što je jednostavno i efikasno rješenje, ali su trofazni pretvarači kojima se distribuirani izvori priključuju na mrežu skuplji od jednofaznih. Kao učinkovito rješenje nameću se i uređaji kojima je moguće priključiti fazu priključenja tereta u mreži ili novog distribuiranog izvora. Takvi uređaji mogu biti statičke ili dinamičke prirode, pri čemu dinamički nude veći broj uklopa, a time i veću mogućnost regulacije naponske nesimetrije. S druge strane, dinamički sklopni uređaji imaju manji životni vijek s obzirom na veću učestalost promjene stanja. Regulacija faznog napona pomoću jalove snage može pozitivno utjecati i na smanjenje naponske nesimetrije tako da se iznos faznog napona približi iznosima u preostalim fazama. Krajnji korisnici mogu pridonijeti poboljšanju nesimetrije u distribucijskom sustavu na isti način kao i poboljšanju napona, promjenom potrošnje upravljivih jednofazno priključenih fleksibilnih uređaja. Tako dolazi do balansiranja potrošnje među fazama, a time se vrijednosti napona u sve tri faze približavaju jedna drugoj što je preduvjet za smanjenje nesimetrije. Također, upravljivo jednofazno punjenje električnih vozila predstavlja potencijalno efikasno rješenje za smanjenje iznosa faktora naponske nesimetrije u mreži.

U najvećem broju slučajeva, distribuirani izvori energije su na mrežu priključeni uređajima energetske elektronike. Također, uređaji već instalirani u mreži su u velikoj mjeri nelinearni. Karakteristika uređaja energetske elektronike, kao i nelinearnih tereta je struja nesinusoidalnog oblika pri višim frekvencijama. Takav oblik struje dovodi do pojave strujnih i naponskih harmonika u mreži. Harmoničko izobličenje napona i struja može uzrokovati brojne neželjene posljedice u pogodnu distribucijskih mreža kao što su povećanje tehničkih gubitaka i neželjena prorada zaštite, ali i rad pojedinih uređaja sa smanjenom efikasnosti. Zbog toga je izrazito važno ograničiti pojavu viših harmonika u mreži. Najveću primjenu u ograničavanju širenja harmonika u mreži imaju aktivni i pasivni filteri koji blokiraju struje viših harmonika te tako posljedično smanjuju i iznose napona viših harmonika te iznos ukupnog harmoničkog izobličenja. Kao efikasno rješenje pokazali su se i transformatori određene grupe spoja, npr. Dyn, koji blokiraju struje viših harmonika nultog sustava. Fleksibilnost krajnjih korisnika u distribucijskoj mreži je također jedno od potencijalnih rješenje za poboljšanje harmoničkih prilika u mreži, ali njezina primjena nije ispitana u tolikoj mjeri kao u slučaju ostalih tehničkih prilika u mreži. Razlog tome je nedirektna veza između opterećenja krajnjih korisnika i viših harmonika u mreži. Međutim, viši iznosi opterećenja u mreži dovode do porasta iznosa struje osnovnog harmonika u mreži. S obzirom na to da se struje viših harmonika često definiraju kao postotne vrijednosti struje osnovnog harmonika, iznos opterećenja krajnjeg korisnika je moguće povezati s pojavom harmonika u mreži. Zbog toga je promjena potrošnje krajnjeg korisnika jedno od potencijalnih rješenja za ograničavanje širenja viših harmonika u mreži.

Iako efikasnija, rješenja zasnovana na iskorištavanju fizičkih uređaja u mreži često su kompleksna i zahtijevaju značajne investicije koje krajnjem korisniku ne mogu donijeti direktnu dobit, a sve je veći broj smjernica prema kojima je krajnji korisnik sam odgovoran za narušavanje vrijednosti pokazatelja kvalitete električne energije te u slučaju pojave nedozvoljenih vrijednosti riskira ograničavanje proizvodnje ili potrošnje ili čak zabranu priključenja na mrežu. S druge strane, fleksibilnost krajnjeg korisnika je koncept koji se sve više istražuje, ali također zahtijeva ugradnju napredne mjerne i komunikacijske infrastrukture koja će omogućiti automatizaciju promjene potrošnje. Krajnji korisnici su često neodlučni oko pružanja usluga fleksibilnosti zbog potencijalnog ugrožavanja ugode te zbog nejasno definiranih financijskih poticaja i dobiti koju će im pružanje fleksibilnosti donijeti. Brojna istraživanja te znanstveni i stručni radovi su usmjereni na rješavanje tih problema i otključavanje punog potencijala krajnjih korisnika priključenih na distribucijsku mrežu.

Rješenja usmjerena na poboljšanje tehničkih prilika u mreži često su implementirana kao dio matematičkog modela optimalnih tokova snaga. Model optimalnih tokova snaga je jedan od najčešće korištenih modela u planiranju i vođenju distribucijskih mreža. Primjena modela uključuje određivanje optimalnog mjesta priključenja i veličine distribuiranih izvora energije, smanjenje gubitaka u mreži, izračun potrebnog iznos fleksibilnosti za uklanjanje tehničkih problema u mreži, optimalno punjenje električnih vozila i sl. Najveći izazov u korištenju modela optimalnih tokova snaga je nekonveksna i nelinearna formulacija koja čini optimizacijski problem kompleksnim, neskalabilnim i računarski neefikasnim i zahtjevnim. Spomenuti problemi se uspješno svladavaju korištenjem matematičkih aproksimativnih pristupa kao što su relaksacije i linearizacije formulacije optimalnih tokova snaga, ali i primjenom algoritama strojnog učenja na rješavanje jednadžbi optimizacijskog problema. Relaksacijski pristupi podrazumijevaju relaksiranje određenih jednadžbi originalnog optimizacijskog problema čime se proširuje područje u kojemu se nalazi optimalno rješenje danog problema. Dvije najčešće korištene relaksacije metode su *Second-Order Cone Programming* i *Semi-Definite Programming*. Relaksacijski pristupi znatno smanjuju kompleksnost i vrijeme izvođenja problema, a za određene funkcije cilja garantiraju točnost dobivene vrijednosti optimalnog rješenja. S druge strane, u određenim slučajevima dolazi do gubitka točnosti rješenja optimizacijskog problema. Drugi često korišteni pristup je lineariziranje određenih jednadžbi koje su dio početne formulacije optimalnih tokova snaga. Unatoč prednostima ovakvog pristupa koji uvelike uklanjaju problema neskalabilnosti, problemi gubitka točnosti koji se javljaju prilikom korištenja relaksacije ostaju neriješeni. Algoritmi strojnog učenja nalaze svoju primjenu i u rješavanju problema optimalnih tokova snaga. Algoritmi strojnog učenja mogu naučiti rješavati kompleksne nelinearne izraze i predviđati rješenja problema. Osim gubitka točnosti, ovakav pristup zahtijeva dostupnog velikog skupa povijesnih podataka što u slučaju niskoosmotrivih distribucijskih mreža nije moguće uvijek očekivati. Kao jedini pristup koji osigurava točnost je korištenje početne nelinearne i nekonveksne formulacije optimalnih tokova snaga. Osim spomenutih problema vezanih uz skalabilnost problema, dodatan izazov predstavlja mogućnost pronalaska lokalnog umjesto globalnog optimuma. Svaki od spomenutih pristupa ima određene prednosti i mane, a odluka o korištenju pristupa ovisi o specifičnostima problema kojeg je potrebno riješiti te o tome pridaje li se veća važnost točnosti optimalnog rješenja ili vremenu u kojemu je potrebno doći do rješenja.

Ključne riječi: distribucijske mreže; distribuirani izvori energije; geografski informacijski sustav; kvaliteta električne energije; optimalni tokovi snage

Contents

Chapter 1

Introduction

1.1 Background and Motivation

The increase in greenhouse gas emissions contributing to climate changes and recent global events that created numerous challenges in the planning and operation of power systems accelerated the green energy transition and the need for energy independence. Different European Union's plans for reaching climate neutrality, such as European Green Deal [1] or Fit for 55 [2], are continuously being adjusted in order to ensure the rise in the share of renewable energy sources (RES) and other low carbon (LC) technologies including electric vehicles (EVs) and heat pumps (HPs).

Besides initiatives and directives aimed at speeding up the integration of RES but also electrification of heating, transport, and other sectors, electricity prices are another significant factor affecting the power system [3, 4]. Fluctuations and increases in prices on wholesale electricity markets in the last few years reflected on the electricity price paid by end-users [5]. Furthermore, gas and oil prices are also affected by the recent global events [6, 7]. Another important trend is the development of technology and the consequential decrease in the cost of investment in distributed energy resources (DERs). The price of photovoltaic (PV) modules has been continuously decreasing [8], making PVs more affordable and profitable due to the shorter time needed for returning the investment. Reduced prices of batteries and EVs in general and advanced and more accessible charging infrastructure are key factors for many end-users that decide to replace their cars with electric ones [9]. Another LC technology with a continuous increase in the market share is HPs, whose costs are decreasing each year, and their lifetime cost is cheaper than oil and gas for heating in several countries [10, 11]. All reports and studies in the field of the integration of LC units in the power system give the same conclusion about significant financial and environmental benefits and the importance of continuing the process of replacing conventional energy sources with new, clean sources.

However, the integration of LC units in the power system, especially in medium voltage

(MV) and low voltage (LV) distribution networks is often uncoordinated, i.e., it is done without a detailed analysis of their impact on technical conditions in distribution networks. Charging of EVs in residential LV networks often corresponds with the peak demand of households, leading to the increased use capacity of lines, cables, and transformers [12]. One of the risks caused by the increasing penetration that needs to be minimised or, if possible, avoided is the occurrence of overvoltage [13]. Besides the overvoltage problem, integration of PVs without a detailed analysis and well-structured plan creates the flow of electricity from end-users to a substation and the increase in network losses once the share of PVs passes a certain value [14]. HPs in LV networks can lead to a decrease in the value of voltage magnitude, an increase in the loading of a transformer in an MV/LV substation, and deterioration of other technical conditions [15]. Without necessary analyses, penetration of DERs will become a problem instead of an opportunity. Therefore, it is of utmost importance to enable distribution system operators (DSOs) and decision-makers to analyse the impact of DERs on technical conditions in distribution networks.

1.2 Objective of the Thesis

There is a lack of tools and developed methods that can be used in detailed analyses and mitigation of problems in distribution networks. Characteristics of MV and especially LV networks require the development of specialised models that can be used both in analyses of networks and improvement of different aspects of planning and operation of distribution.

Despite the digitisation and increased observability in LV networks, data about the network topology and end-users' consumption measurements often contain numerous errors, making them unusable in the initial form. Since distribution network data is being more represented using geographic information system (GIS), a significant number of errors is related to common geospatial problems. However, using GIS also presents an opportunity since advanced geospatial queries can be applied to removing errors at their source. Once the data processing is finalised, GIS data can be used in creating the model of a real-world LV distribution network and its mathematical representation.

Once the model of an LV distribution network is successfully created, it can be connected to other sources of information such as smart meter measurements. Once all necessary information is collected and all data is processed, it can be used as input into tools used in simulations and analyses of LV networks. Widely-used commercial software tools are often limited in available functionalities and can be used only for basic analyses of the power system. However, the changes in distribution networks create the need for additional analyses that previously were irrelevant in the planning and operation. Therefore, the use of open-source tools is increasing, and even though some still have a limited set of functionalities, they can easily be upgraded and extended. One of the raising issues caused by the integration of DERs is the deterioration of power quality (PQ), with the values of indicators violating the defined limitations.

In a lot of cases, analyses will show the existence of technical problems in LV distribution networks. Therefore, the next step is the implementation of models aimed at solving the problems occurring in the planning and operation of distribution networks. Lately, end-users potential to provide flexibility services is being more recognized. However, the flexibility needed to reduce PQ disturbances is not used as a solution enough. The rare cases of analysing the role of end-users in the PQ improvement are done in representative cases or in a controlled laboratory environment. Still, most improvement methods are based on the implementation of physical devices that can often be expensive and require additional investments.

To summarize, the number of models used in the planning and operation of distribution networks with a high share of DERs is continuously growing. Developed models must be intuitive and easy to understand, but they should also have the possibility of upgrading and adjusting to new requests by DSOs and other decision-makers. The objective of this thesis is to propose and evaluate developed innovative models that enable easier and more advanced analyses of distribution networks and the mitigation of technical problems caused by the uncoordinated integration of DERs:

- The method for removing detected errors in the initial GIS data set is developed and structurally presented. The method is based on the geospatial characteristics of the data, and once all errors are removed, GIS data is used to create a mathematical representation of an LV network.
- Optimal power flow (OPF) formulations are commonly used in solving different problems in LV distribution networks. However, existing OPF formulations do not consider PQ limitations as one of the constraints in the optimisation problem. Therefore, the existing non-linear three-phase OPF formulation is extended with voltage unbalance and harmonic constraints.
- Flexible end-users can shift their demand in order to help mitigate technical issues in LV networks. However, such approaches can often disrupt their comfort, making them unwilling to provide flexibility services in the future. The proposed method determines the needed change of demand while considering the comfort of end-users.

The scientific contribution of the thesis is divided into three parts:

1. Method of detecting and removing errors in the geographic information systems data that enables the automated initialization of advanced calculation parameters in distribution network.
2. Three-phase optimal power flow model with included harmonic and voltage unbalance constraint.
3. Method for determining the needed end-user's change of electricity consumption for providing services of the power quality improvement.

1.3 Structure of the Thesis

The thesis is structured as follows:

- Chapter 2 describes the approaches used to create a network model in cases when network data is not available, how GIS data is used in creating a model of a real-world network, and the difference between different ways of creating a mathematical representation of a network.
- Chapter 3 gives an overview of tools used for power system simulations, the results of PQ analyses and methods for the improvement of PQ based on both the utilisation of physical devices and the flexibility of end-users.
- Chapter 4 presents differences between different OPF formulations, potential issues in using each of them, and the detailed mathematical formulation of the non-linear three-phase OPF formulation extended with voltage unbalance and harmonic constraints.
- Chapter 5 highlights the main contributions presented in the thesis and how they are realised in related publications.
- Chapter 6 presents the list of all relevant publications.
- Chapter 7 summarises the author's contribution to the publications.
- Chapter 8 concludes the thesis, highlights the main findings, and proposes the direction for future work.

Chapter 2

Modelling of Distribution Networks

Having an exact representation of a distribution network's model is a prerequisite for analyses and simulations of power systems. However, publicly available models of transmission networks cannot be used due to specific characteristics of distribution networks, including the higher R/X ratio of lines and cables, radial network topology, the need for three-phase models of network, but also others that create the need for specific models [16].

Another characteristic of distribution networks, in general, is their low observability. This low observability leads to the lack of mapping of distribution, especially low voltage (LV) networks and the lack of measurements that prevent execution and real-time actions needed to ensure safe and reliable operation of distribution networks [17]. The focus of the thesis is on the problem of the complexity of creating distribution network models and not on the problems created by insufficient share of installed advanced metering infrastructure in distribution networks.

2.1 Representative Network Models

To overcome the issues created by the low observability, researchers, system operators, and other relevant entities created a significant number of representative synthetic networks that can be used in different distribution network analyses [18]. The importance of representative networks is recognized by the European Commission in the report providing the guideline with all the steps and required data that need to be collected for the successful creation of representative networks [19]. The authors of the paper [20] present an algorithm that is used to create a large-scale data set that consists of 10 million nodes and more than 120 000 km of power lines. Distribution networks' data provided by 79 Distribution System Operators (DSOs) is used to create a methodology that is a basis for creating nine representative large-scale distribution networks and feeders [21]. A similar approach is presented in the paper [22], in which a specific representative network is created based on a defined set of parameters. A created representative network can afterwards be used in different analyses of distribution networks, e.g., the assessment of the impact of different shares of PVs on voltage deviation and line losses [23]. The MATLAB-based toolkit named AutoSynGrid automatically generates any number of synthetic power grids with the same characteristics as realistic power grids including topology, bus type, generation capacities, load settings, etc. [24]. Another MATLAB-based tool, TDNetGen, is developed by Pilatte *et al.* [25]. TDNetGen can be applied in generating synthetic integrated transmission and distribution network models that are used in analysing the interaction between the two systems, e.g., the provision of flexibility by active distribution networks or the co-optimisation of planning and operation. Even though the relevant papers and reports, in most cases, provide data for creating a representative model that can be used in various analyses, research is in some cases oriented on developing models for a specific analysis. The method presented in [26] selects only a few LV distribution feeders with an appropriate set of characteristics determined by clustering. The selected set of feeders represents the scaled LV network and is used in solving the PV hosting capacity problem for the whole network. With the increase of non-linear loads and power electronic devices, harmonic distortion becomes a relevant problem for DSOs. The problem with the lack of measurements becomes even more emphasized in the harmonic analysis since capturing the harmonic spectrum requires the installation of additional metering devices. To overcome some of the obstacles, the IEEE-PES Task Force on Harmonics Modeling and Simulation created a benchmark test system representing an MV/LV network supplying an industrial consumer [27]. The main goal of the system is to provide support for investigating different methods for determining the contribution of higher-order harmonics. Due to many different approaches to creating representative networks, Guo *et al.* recognised the need to present a structured summation of published research and present collected topology and techno-economic networks' data [28]. The most significant benefit of representative network models is their use in the verification and testing of developed models aimed at the improvement of planning and operation of distribution networks. However, whenever they are used in simulations and analyses, only general conclusions can be drawn. A conclusion related to the specific case requires the exact real-world model of a network.

2.2 Real-world Network Models

Even though representative network models are often based on real-world data, they are created using statistical methods and clustering techniques. Such solutions represent the most common network or a network, with the characteristics most similar to the majority considered networks. Cases in which models of all observed networks are known and available create an additional set of test systems but also present an opportunity for a DSO to be able to analyse actual conditions without making unrealistic assumptions. A non-synthetic European LV network with

10 290 nodes, 8 087 end-users, and 30 power transformers is presented in [29], together with MATLAB functions for creating and running the OpenDSS model. The network is created from the raw geographic information system (GIS) data and collected smart meter measurements. Crossland *et al.* were able to extract over 9 000 real-world LV network models relying on the GIS data stored in a DSO's database [30]. Extracted networks are then used to find an optimal location for installing home battery storage to prevent overvoltage problems. With the recent digitisation, GIS data is being more used in the mapping of distribution networks. Besides geospatial information, GIS data contains technical information about power system elements, such as the resistance and reactance of a line or cable or the power of a transformer. For that reason, GIS data is the basis for modelling distribution networks. However, the flaw of GIS data is that their initial form contains a lot of errors that prevent their exploitation in creating real-world network models. An additional problem with GIS data is that each set contains its own set of errors, and developing a common automated method for removing the detected errors is almost impossible. Navarro-Espinosa *et al.* focused on resolving connectivity issues in collected GIS data [31]. The successful application of the proposed reconnection methodology enables the creation of network models, afterwards used in power flow simulations. Besides connectivity problems, other GIS problems preventing the creation of network models are investigated in [32]. The problems include detecting meshed networks in radial systems, LV networks with multiple transformers, disconnected transformers, disconnected loads, and incomplete secondary systems. The authors propose a methodology relying on QGIS and Python, aimed at automated correction of identified errors. Montano-Martinez *et al.* propose an optimization algorithm for correcting the coordinates of an LV network's element. The procedure helps assign loads and DER nodes to their corresponding customer location determined by the parcel coordinates. The presented correction of GIS data enables easier and more precise connection of smart meter measurements with an LV network topology. The integration of Python, SQL, and QGIs for correcting several errors in GIS data is presented in [33]. After removing the detected errors, including the continuity of a polyline, disconnection of elements, unknown beginning and ending nodes of LV cables and lines and others, an LV network model is created using the pandapower simulation tool. Having GIS data without any errors is a prerequisite for different analyses of distribution networks, such as the assessment of the networks' ability to host rooftop PV systems [34]. However, even in cases without any GIS data errors, creating a network's mathematical representation is not always intuitive. It is possible to create a network by connecting GIS data to power system simulation tools such as OpenDSS [35]. Once the network is created, it can be directly used in power flow or other similar simulations. Due to the limitations of power system simulation tools, some specific analyses require the development of new tools, and in those cases, the mathematical model of a network needs to be created by following the common modelling rules that respect the specific characteristics of different

network types and topologies.

2.3 Mathematical Model of a Distribution Network

The mathematical model of a balanced power system is easy to create and does not require a lot of information contained in the technical attributes of GIS data. However, this assumption is valid only in specific cases of transmission and MV distribution networks. Even though there are attempts to apply such network models in LV network analyses, single-phase loads and other characteristics make the balanced modelling approach inaccurate. Technical attributes of LV lines and cables contain information about their type, i.e., positive and zero sequence system resistance and reactance, geometry, maximum allowed current, etc. Relying on the known values of those parameters, it is possible to create an impedance model that is the essential part of the network model. One of the common approaches is using symmetrical components for transforming values of positive, negative, and zero sequence systems to phase values [36]. Despite being the most convenient approach, its use brings modelling assumptions that lead to the loss of accuracy, which is still smaller than assuming a perfectly balanced network [37, 38]. One of the most common methods for creating the impedance method presented by Carson is based on the conductor imaging method to calculate the impact of the ground return current [39]. Modification of Carson's method for its application in distribution network studies in which the ground is explicitly represented is discussed in [40]. Carson's method is one of the basic impedance modelling methods further modified in many studies, including the one presented by Kersting and Phillips, who presented a set of new equations for self-impedance and mutual impedance of conductors [41]. Further modifications include applying Kron's reduction technique aimed at decreasing the dimension of a conductor's impedance matrix from 4x4 to 3x3 [42]. More recent upgrades of Kron's reduction include graph-theoretic analysis considering topological, algebraic, spectral resistive, and sensitivity analyses [43]. The conducted analysis leads to novel insights both on the mathematical and the physical side. In order to decrease the number of voltage variables and increase the computational speed of solving optimisation problems in LV networks, Geth *et al.* presented a novel, highly accurate reduction technique, which is shown to be a good approximation in comparison to some other approaches [44]. Another reduction method proposed for European style TT grounded low voltage networks is proposed in [45]. The major benefit of this approach is that it does not rely on Carson's method, making it applicable in cases when geometry data is not available. No matter the approach, impedance modelling is one of the most important steps needed to be completed before further simulations. Many different modelling techniques are widely used, and no matter the potential loss of accuracy, they are applied in simulating a wide range of scenarios and test cases that help in the assessment of DERs on technical conditions in LV networks.

2.4 Connection to the Contributions

The development of tools and methods used in power system analyses is becoming more important for DSOs due to the constant changes caused by the change in end-users' electricity consumption and integration of DERs. However, distribution networks are characterised by low observability, which leads to the unavailability of relevant data. In those cases, DSOs, policy-makers, and research often rely on representative, benchmark distribution network models, which make the conclusions general and not specific for a certain case, as shown in Section 2.1.

However, recent digitisation and the development of information technology have led to the application of GIS in distribution network mapping. Besides providing relevant geospatial, GIS provides information about the technical characteristics of distribution network elements. However, GIS data often requires processing due to the errors in the initial data set. Section 2.2 gives an overview of some common issues in the GIS data set, but also some approaches in removing errors and preparing data for further distribution network simulations.

Benchmark network data or GIS data used in different distribution network analyses need to be represented with valid mathematical equivalents of a network. Section 2.3 provides a review of different approaches for creating the mathematical representation. The first approach is the direct use of data in power system simulation tools that already have implemented methods for transforming network data into a network representative model. Such an approach is used in developed methods and conducted analyses presented in the rest of this thesis. The other approach is more detailed and studies the potential loss of accuracy when introducing approximations and using less complex models.

Chapter 3

Power Quality in Distribution Networks

Power quality (PQ) is defined in many ways, but almost all definitions agree that it is related to any voltage, current, or frequency deviation that leads to failure or malfunction of the equipment in power systems [46]. Furthermore, the International Electrotechnical Commission (IEC) defines PQ in the group of standards 61000 as a set of parameters defining the properties of the power supply as delivered to the user in normal operating conditions in terms of continuity of supply and characteristic of voltage (magnitude, frequency, waveform). The focus of the thesis is on the characteristics of voltage, more precisely voltage magnitude, voltage unbalance, and harmonic distortion, since these are the PQ indicators that can be calculated using quasi-static time series simulations. Important standards such as IEC 61000-2-2 [47], IEC 61000-2-12 [48], EN 50160, and others define the threshold values for each of the indicators, but also the percentage of time in which the values of indicators need to be within the allowed interval [49]. Another important document that defines threshold values of PQ indicators in the Croatian distribution grid code [50]. As defined in the relevant standards and Croatian distribution grid code, the value of voltage magnitude needs to be between 90% and 110% of the nominal voltage, voltage unbalance factor (VUF) must be below 2% (3% in distribution networks with predominant single-phase connected loads), while the value of total voltage harmonic distortion (THD_u) is limited by 8%. All of these constraints need to be satisfied for 95% of observed weekly values over 10-minute periods.

With the integration of DERs, keeping the values of PQ indicators within an allowed interval is becoming more of a challenge for DSOs. Decreasing PQ deterioration often requires the installation of additional devices or the implementation of complex methods and solutions. However, poor PQ creates increased economic costs and financial losses, causes a failure of the equipment and shortens its lifetime. Residential end-users face different consequences related to PQ disturbances, e.g., high electricity bills or blown fuses in the case of harmonics, overheating of motors caused by unbalance, etc. [51]. The authors in [52] provide a summary of the economic impact of poor power quality on end-users. The costs can be broken down into direct, indirect, and social-economic costs, and they include additional energy losses, additional loading and damaging of components, and other costs caused by voltage magnitude, voltage unbalance, harmonics and other PQ disturbances. However, fully understanding the economic impact of poor PQ on end-users and networks is still challenging, and there are many projects oriented toward PQ monitoring with one of the goals of better recognising the obstacles related to PQ economics [53].

To avoid the unwanted effects of the DERs' integration, it is important to analyse their impact on technical conditions in a network. Furthermore, in cases of PQ deterioration, the values of analysed PQ indicators need to be improved. All of that is not possible without simulating the conditions in a network using power system simulation tools.

3.1 Power System Simulation Tools

Power system simulation tools can be divided into those based on the graphical user interface, which are in most cases commercial and licensed, and those based on programming languages that are in most cases open source but also without the possibility of visualizing the network elements which often makes them not intuitive [54, 55].

3.1.1 Commercial Simulation Tools

NEPLAN Electricity is a software tool to analyse, plan, optimize and simulate electrical networks with a user-friendly graphical interface. Mimica *et al.* verified the results of the capacity expansion energy planning model by the comparison with a detailed transmission and distribution network analysis carried out in NEPLAN [56]. Due to the high number of new types of loads and the increased measurements, an aggregated model formulated for dynamic simulations of power systems is modelled in [57]. To verify the accuracy and investigate the capabilities of the presented model, the authors performed several simulations using NEPLAN. PowerFactory is another power system analysis software used in analysing generation, transmission, distribution, and industrial systems. Barać *et al.* used PoweFactory to test grid-forming converter control schemes for power system fundamental frequency dynamic simulations by using an example of a virtual synchronous machine [58]. Moreover, the presented model is made publicly available in the PowerFactory format. Another application of PowerFactory is presented in [59], in which the authors use PowerFactory to develop, analyse, and test the power system to determine the optimal allocation of energy storage for the improvement of performance and power quality of distribution networks. Even though ETAP provides a similar set of functionalities as other simulation tools, most published papers use it in calculating fault-related events. ETAP was used in analyses of an IEEE 9-bus system with added PVs in determining the microgrid protection using an optimal coordination scheme and nonstandard tripping characteristics [60]. However, the ETAP simulation tool can be used in other types of analyses. e.g., Tan Turan *et al.* calculated daily change in power consumption, reduction of power losses, decreased main feeder ampacity, and restoration of voltage level during the operation of PV power plant and charging of EVs [61]. Power flow simulations can also be run using PSS/E, as shown in [62], in which the authors use the proposed wind generator model created by the artificial neural network. PSS/E is also used in cascading failure analysis under different loading conditions in a real-world Indian power system [63].

Above mentioned but also other similar commercial power system simulation tools are used for their reliability and high number of available functionalities. Also, the results obtained with simulations do not need to be verified, and the graphical interface makes them easy to use and understand. Therefore, they are widely used in numerous power system analyses. On the other hand, they often require expensive licenses, are hard to connect with other tools and external databases, and are almost impossible to upgrade with new functionalities, which is becoming more important due to constant changes in distribution networks. For that reason, researchers are more often turning to open source simulation software, which is often based on different programming languages.

3.1.2 Open Source Simulation Tools

MATPOWER is one of the first open source power system simulation tools, developed as a Matlab package [64]. It provides various functionalities such as power flow simulations and both AC and DC optimal power flow simulations, but also others targeted toward researchers, educators and students. Since the MATPOWER tool is based on the Matlab programming language, it is possible to extend its range of functionalities and adjust them to be suitable for different important power system analyses, such as the harmonic power flow analysis [65]. Python is a programming language suitable for applications in engineering and Thurner *et al.* developed pandapower, a Python library aimed at the automation of static and quasi-static analysis and optimization of balanced power systems. It provides power flow, optimal power flow, state estimation, topological graph searches, and short-circuit calculations according to IEC 60909 [66, 67]. Same as in the case of MATPOWER, developing pandapower as a Python package allows the extension of the functionalities that it provides [68, 69]. In recent years, Julia has emerged as a high-level programming language for numerical computing. Optimisation approaches are becoming more important in the planning and operation of distribution networks and models implemented in Julia are being recognized as a solution for the newly created problems. PowerModels is an open source toolkit built on top of the Julia programming language for optimisation of power systems [70]. The focus of the toolkit is on comparing different power flow formulations, including AC polar, AC rectangular, DC approximation, SOC relaxation and QC relaxation. Following the Julia implementation of PowerModels, Fobes *et al.* present PowerModelsDistribution, Julia toolkit with integrated algorithms for OPF of unbalanced distribution network [71]. Same as in the case of PowerModels, PowerModelsDistribution offers several implementations of power flow and OPF formulations. Other than open source tools developed as programming language packages, there are several tools with similar logic but developed as tools on their own, without the connection to any programming language. One such tool is OpenDSS, an electric power distribution system simulator (DSS) designed to support DERs grid integration and grid modernisation [72]. OpenDSS is applied in solving numerous distribution network problems, e.g., quasi-static time-series power flow solution for islanded and unbalanced three-phase microgrids [73] or determining maximum EV hosting capacity of low voltage distribution networks based on the Monte Carlo simulation [74].

As seen from the review of open source power system simulation tools, their biggest advantage is the availability and possibility to adjust and extend them with the new set of needed functionalities. Moreover, they can be easily integrated with other software and external databases. However, their use is not as intuitive as the use of commercial simulation tools, mostly due to the lack of a graphical interface. Despite the mentioned problem, the constant changes in distribution networks create the need for the continuous development of new functionalities and tools that will enable analyses in the planning and operation of distribution networks.

3.2 Power Quality Analysis and Improvement

PQ analyses are becoming a crucial part of the planning and operation of distribution networks. Based on the available functionalities and user preferences, different simulation tools are being used in three-phase power flow simulations to calculate values of voltage magnitude and VUF and harmonic power flow simulations to calculate higher-order harmonic voltages and THD_u. Recently, base PQ analyses in distribution networks have been accompanied by methods oriented towards one or multiple PQ indicators' improvement. Since the PQ deterioration presents a potential financial loss and planning and operational risks for DSOs, the PQ indicators' improvement in distribution networks is becoming recognized as an important process worth investigating and implementing, especially due to increased PQ disturbances caused by the uncoordinated integration of DERs. Improvement methods can be oriented on the installation and utilisation of physical devices and exploitation of end-users potential in providing flexibility services. Both approaches are shown to be efficient and are becoming widely used in mitigating different technical issues in distribution networks.

3.2.1 Overvoltage

Peak generation of PVs often corresponds to low values of demand in LV networks, creating a local disbalance between generation and consumption. In those cases, voltage magnitude rises, creating the risk of overvoltage [75]. It needs to be emphasized that PVs are not the only cause of overvoltage in distribution networks as shown in [76], where the authors analyse temporary overvoltage created by different inverter-based DERs however, the effect of PVs integration is the most investigated in distribution and especially LV networks.

Solutions oriented on physical devices often include the of inverters, either through Volt-Var control in which inverters absorb reactive power to lower the value of voltage magnitude [77] or active power curtailment, a solution in which output power of a PV system decreases to a level that brings voltage magnitude below the upper limit [78]. Other solutions that rely on utilising physical devices include coordinated work of a PV system and other DERs, with the goal of minimising the negative impact of excess generation. Installation of battery storage at the PV generation sites is often a part of approaches for mitigating PV-caused overvoltage. Due to the high cost of battery storage, the capacity of ones installed in a distribution network is sometimes not sufficient to allow charging whenever the PV generation exceeds total demand. The approach proposed in [79] maximises the use of batteries from other regions to provide voltage regulation aimed at avoiding overvoltage problems. Batteries can also be a part of flexibility schemes in cases when they are located at the end-user site and when they are used to increase the potential of their demand change. Using different types of active transformers can also be an efficient solution in solving overvoltage problems in distribution networks, as shown by Mawarni *et al.* who present the potential benefit of using an on-load tap changer transformer [80].

End-users connected to a distribution network can often help in mitigating the technical problems in a network by changing the consumption of flexible and controllable loads. As mentioned before, overvoltage is caused by excess PV generation, and end-users can participate in voltage regulation by increasing demand when necessary. Chen *et al.* consider several different smart thermal loads whose demand can be changed according to the needs in a network, with an optional energy storage system [81]. The results of the analysis prove the proposed method to be efficient and environmentally friendly in preventing overvoltage in an LV network with a high share of PVs. Electric water heaters are also considered as flexible loads in [82], in which they are controlled to minimise the peak imports and exports of the observed area, through which the reduction of voltage fluctuations caused by PVs is also provided. Even though electric water heaters can also be categorised as physical devices, they are loads that are part of a household and the potential change in their demand leads to the possibility of providing the requested flexibility service by an end-user. The same situation is with EVs, and in cases when they are owned by end-users located in an LV network, their controlled charging is the change in the total demand of an end-user, which can prevent overvoltage caused by PVs [83]. Flexible resources are activated for voltage regulation in the case of the overvoltage occurrence based on the two-step demand response (DR) scheme [84]. The first stage is the day-ahead scheduling stage, in which flexible resources are scheduled to minimise end-users electricity costs and voltage violation time, and the second stage is the real-time operation stage aimed at eliminating voltage violations.

3.2.2 Undervoltage

Contrary to the voltage increase caused by the integration of photovoltaic panels, some DERs such as EVs or HPs increase the total demand in distribution networks and consequentially result in voltage drop, large enough to cause undervoltage problems [85, 86]. Approaches for mitigating this specific problem are oriented toward utilising physical devices or exploiting end-users flexibility potential, the same as in the case of preventing overvoltage.

Capacitor banks are often used in voltage regulation in distribution networks. Due to the complexity of determining the optimal placement and number of capacitor banks in a distribution network, a novel metaheuristic technique is used to solve the problem [87]. The used approach is proven to be efficient in the improvement of voltage profile but also in decreasing power losses in a distribution network. Islam *et al.* proposed a method that considers a coordinated operation of battery storage and capacitor banks for mitigating issues in distribution networks, including voltage drop [88]. Inverters that are the interface between a DER and a grid can also be used in providing voltage regulation services. One such approach is proposed in [89], in which the authors enable local voltage control by a shunt-connected energy storage system that uses both active and reactive compensation currents. The proposed methodology is shown to be efficient in solving different voltage regulation problems, including unbalanced voltage drops.

In the case of undervoltage caused by EVs, smart charging of EVs is shown to be an efficient solution in preventing the created problem. Wang *et al.* propose a two-level distributed coordinated voltage control scheme that determines the output of both active and reactive charging power output to ensure the values of voltage magnitude will not violate the threshold value in a tested LV network [90]. The results of research presented in [91] show that smart charging of EVs is not only efficient in mitigating undervoltage problems but also in the improvement of EV hosting capacity due to improved nodal voltage profiles. The results of the important investigation of the impact of EVs on the operation of LV networks are presented by Quiros-Tortos *et al.* [92]. The trial results show the impact of uncoordinated EV charging on the undervoltage occurrence, but also that smart strategies can prevent the potential problem and additionally increase the share of EV charging stations in a network. Besides relying only on smart charging strategies, activation of end-users flexible loads is also efficient in mitigating undervoltage.

The same approach used for decreasing too-high values of voltage magnitude is also applied to increasing too-low voltage values, with the opposite direction of the consumption change [84].

3.2.3 Voltage Unbalance

Even though end-users can be both single-phase and three-phase connected to a network, most of their devices are single-phase. The same situation is with DERs since their single-phase installation is less complex and expensive. Therefore, there is a possibility of an unbalanced distribution of demand among the phases, and consequentially, the occurrence of voltage unbalance in a network, e.g., integration of PVs besides overvoltage problems creates those related to voltage unbalance [93]. Increased voltage unbalance negatively affects the operation and usage of motors, lines, cables and other equipment installed in distribution networks [94]. Furthermore, Ochoa *et al.* determined a correlation between the increase in unbalance and network losses, where network losses are higher for 4.1% for a 15% unbalance in comparison to a fully balanced network. To prevent the negative impact of voltage unbalance, it is important to decrease the value of VUF below the defined threshold values.

Besides Volt-Var control aimed at regulating voltage deviation caused by PVs, the same inverter-based approach is used for mitigating voltage unbalance in an LV distribution network [95]. Besides regulation of only reactive power, Brandao *et al.* propose a multiobjective approach that also regulates the active power of distributed generators [96]. Even though the proposed approach is oriented toward minimising current unbalance, it can be applied in minimising voltage unbalance due to the correlation of voltage and current. Besides using inverters of DERs themselves, inverter-based static compensators are another solution for minimising unbalance in a network, as shown in [97], in which the authors propose three control schemes aimed at compensating the unbalance of voltage, current, or both. Besides the use of inverters, another device applied to minimising voltage unbalance is a phase-switching device. The authors of paper [98] present a genetic algorithm-based solution for the optimal placement of static switches in an LV distribution network. The solution determines the connection phase of a PV system, leading to minimum total energy losses caused by current unbalance, the minimum number of switches, and voltage unbalance within the acceptable range. Besides the placement of static switches, another approach that relies on switches considers dynamic re-phasing of PVs, which is shown to be a more efficient solution due to a higher number of periods in which unbalance needs to be reduced [99]. Besides switching the connection phase of DERs, it is also possible to decrease voltage unbalance by changing an end-user's connection phase. Shania *et al.* presented the central controller that observes consumption in each household and determines which end-users need to be transferred from the initial phase to another using static transfer switches [100].

The solutions based on activating end-users flexibility are similar to those used in mitigating voltage fluctuation problems, i.e., they are oriented on the change of demand in the most convenient way for decreasing voltage unbalance in a distribution network. DR in distribution networks can be complemented by implementing Volt-Var control using the minimum number of devices [101]. The encouraging results show the efficiency of the proposed model and the benefits of the combined approach in the improvement of several technical quantities, including voltage unbalance. Another approach for minimising voltage unbalance relying on the coordinated operation of end-users flexibility and physical device, which is a tap changer transformer, in this case, is investigated by Rahman *et al.* [102]. The method is tested on a real-world Australian LV network with a high share of PV rooftop generation, and the results show that it is possible to avoid both critical voltage magnitude and unbalance violations while simultaneously enabling the further increase of PV integration. Thermal loads are often modelled as flexible resources in LV distribution networks. However, a change in their demand can cause a loss of comfort for end-users who might reconsider their participation in providing flexibility resources. Therefore, the voltage-dependent thermal load model extended with the control strategy for mitigating voltage unbalance that also maintains the end-users thermal comfort is presented in [103]. Thermal loads often used for demand-side management are considered controllable loads and flexible resources in the control algorithm based on voltage sensitivity [104]. The performed analysis shows that it is possible to lower the VUF value together with the number of controlled thermal loads in a network. Growing application of machine learning algorithms has also shown promising results in the area of mitigating voltage unbalance as proposed by Bera *et al.*, who use deep learning to optimally aggregate controlled thermal loads in a microgrid to minimise voltage unbalance [105].

3.2.4 Harmonic Distortion

Nonlinear loads contribute to the total demand of each end-user connected to a distribution network. Additionally, the interface between most DERs and a distribution network is based on power electronics. Both nonlinear loads and power electronic devices are sources of higher-order harmonics contributing to total harmonic pollution in distribution networks. Since the negative effects of harmonic distortion include the increased losses of rotating machines, negative impact on transformers and end-users equipment, interference with protection devices, but also other potentially harmful problems, it is important to minimise the distortion and mitigate harmonics whenever needed [106].

As DERs are identified as harmonic sources, it is important to ensure the needed harmonic compensation at the source of the harmonic problem. Despite the nonlinearity of inverters' current, they are controllable and can be used as a part of a solution, as shown in [107], where the authors present a coordinated control of four-leg inverters for harmonic mitigation in LV networks. The model of a synchronous static compensator is therefore developed and tested to investigate the efficiency in compensating higher-order harmonics in an LV network [108]. Harmonic compensation and mitigation techniques often rely on integrating active and passive filters. The same as in the case of determining the optimal number of switches needed for minimising voltage unbalance, the location and number of needed filters is a complex problem. To avoid the problem, Bagheri *et al.* propose a method that places the filters in randomly selected nodes in a residential distribution network and focuses on the configuration of filters instead [109]. The results show that the investigated method can be efficient in reducing the harmonic distortions in selected areas of a distribution system. However, there are examples in the literature in which optimal sitting and sizing of filters are investigated. The method based on a genetic algorithm and Monte Carlo simulations is used to compute the number and locations of passive filters in an LV distribution network with a high share of PVs [110]. Moreover, the authors consider economic analysis, including loss reduction benefit and passive filter costs, and take into account both higher-order harmonic phase angles and currents. The vector group of a transformer in distribution networks plays an important role in constraining harmonic propagation in a network, e.g., the Dyn vector group blocks the flow of the zero sequence harmonic current. Some approaches complement the described decrease of harmonic pollution by additional harmonic filters that will only contribute to a further decrease. Zhang *et al.* developed an approach in which they establish the schemes of an induction filter distribution transformer and filters in an LV network and afterwards consider the harmonic contribution of both load and network side, based on the winding of a transformer [111]. The results of a study show the efficiency in providing both harmonic and reactive power compensation. Another approach in which distribution transformers are complemented with filters is presented in [112]. The authors analyse the influence of potential manufacturer's error on a transformer's winding and, based on the results, propose a method for determining the optimal performance of a filter.

Solutions that use the flexibility potential of end-users are not as investigated as those based on the installation of often costly physical devices. Implementation of household appliances demand shifting is presented in [113], where the strategy is tested in the laboratory environment using collected real-world measurements to decrease the value of THD. Another DR program is proposed by Devarapalli *et al.*, who explore a non-intrusive load pattern identification that proposes the combination of loads that reduces harmonic injection into a network [114]. In the thesis [115], a DR scheme with the minimum inconvenience of end-users is tested on a real-world urban distribution network in the analysis of harmonic distortion. The harmonic mitigation method based on a genetic algorithm with the possibility to solve multiple, even competing objectives, is presented in [116]. The method is tested on a small industrial grid where the optimisation process decreases the value of THD in all nodes without the loss of productivity of the industrial process.

3.3 Power Quality Analyses Presented in the Thesis

All calculations are conducted using power system simulation tools, shown in Section 3.1. Subsections 3.1.1 and 3.1.2 give an overview of commercial or open source simulation tools. Based on the detailed investigation of their advantages and shortcomings, the focus in this thesis is put on open source simulation tools, their use in power quality analyses and their potential use in the improvement of PQ disturbances in DERs-rich distribution networks.

As mentioned in section 3.2, PQ deterioration is becoming more of a problem for DSOs due to its negative effects on distribution network operation. The focus of this thesis is on quasi-static time series simulations using pandapower and extensions developed as a part of the thesis. Subsections 3.2.1-3.2.4 present more detailed issues caused by overvoltage, undervoltage, voltage unbalance, and harmonic distortion. Besides basic analyses, the thesis also provides a review of methods oriented towards improving the value of each mentioned PQ indicator. Two identified approaches rely on utilising physical devices and activating the end-users flexibility potential. Each of the approaches has certain benefits but also several shortcomings. This thesis focuses on the solutions based on activating end-users' potential and comparison with the simple methods utilising devices in terms of the solutions' efficiency.

Chapter 4

Optimal Power Flow Formulations in Distribution Networks

As shown in Chapter 3, most methods for the device-based PQ improvement require high investment costs, and changing the real-world model of power electronic and other utilised devices can become complex both for researchers and, more importantly, for DSOs. DR-based solutions are often less expensive since they rely on the utilisation of devices already installed in a network and advanced metering and communication infrastructure, which share is growing with the increase in the distribution network's observability. End-users' flexibility is often integrated into different network models and analyses using the optimal power flow (OPF) formulations.

OPF formulations are one of the most used models in different analyses of distribution networks and power systems in general. Exact OPF models are often complex and not easy to solve, and extending models with uncertainties or new entities, e.g., renewable energy sources (RES) or other low carbon (LC) units such as electric vehicles (EVs) or heat pumps (HPs), additionally aggravates solving of the optimisation problem. Therefore, there are numerous approaches that include approximation, relaxation, or linearisation methods that are applied in alleviating the complexity of an OPF problem. However, using such approaches leads to the loss of accuracy due to made assumptions or the neglect of several technical constraints. Therefore, exact nonlinear OPF formulations are the only ones that guarantee the exact optimal solution. The problem with nonlinear formulations is the complexity that often makes the optimisation problem unscalable and intractable. Tractability and scalability problems in power systems are being solved by machine learning (ML) algorithms, and solving OPF problems is not an exception. The problem with ML algorithms is that they are also not 100% accurate and, in some cases, require a high number of historical measurements for training and validating the model.

4.1 Relaxation

Convex relaxations of AC OPF problems are commonly used approaches to alleviate the complexity of distribution network optimisation problems. There are many different relaxation approaches [117], but the two dominating in the field are second-order cone (SOCP) [118] and semi-definite (SDP) [119]. One of the problems with relaxing AC OPF problems is that it leads to a loss of accuracy, and that is not exact for all objective functions [120]. Therefore, one of the most investigated research directions is the development of mathematical models that improve accuracy and guarantee the optimal solution while solving the AC OPF problem.

Venzke *et al.* use the SDP relaxation of chance-constrained OPF, guaranteeing the global optimum of the optimisation problem [121]. Optimality is guaranteed using a piecewise affine policy that ensures tractability, accurately modelling large power deviations and determining suitable corrective control policies for active and reactive power and voltage. Investigation of sufficient conditions making the SOCP relaxation exact is presented in [122]. After identifying the condition of the allowed reverse power flow that can be only reactive, active, or none, the authors prove the exactness of the solution, which ensures that it can be converted to an optimal solution of the original AC OPF. A detailed assessment of the accuracy of the optimal solution using relaxation approaches is presented in [123]. After the in-depth assessment, Venzke *et al.* investigated the most promising AC feasibility recovery methods for large-scale systems and proposed two new metrics that lead to a better understanding of the quality of the identified solutions.

Relaxation methods are becoming even more important in the case of three-phase networks due to larger and more complex network models that make the AC OPF problem even computationally harder to solve. Even though there are methods focusing on investigating sufficient conditions that guarantee the feasible and optimal solution, identifying feasible OPF solutions remains hard in unbalanced multi-phase systems with renewables. To tackle the problem, the Feasible Point Pursuit - Successive Convex Approximation algorithm, an approach for general nonconvex quadratically constrained quadratic programs (QCQP) is proposed in [124]. Another potential problem in the unbalanced distribution network is the type of load modelled in the AC OPF formulation. Zhou *et al.* propose a three-phase AC OPF method that successfully mitigates the inexactness of the SDP relaxation introduced in the case of delta load models [125]. In simulations of different defined case studies, the algorithm provides the exact optimal solution, both in the case of the wye and delta load models. Another study investigating the impact of a wide variety of load models, including constant power, constant current and exponential load models, on the exactness of the AC OPF relaxation is presented in [126]. Moreover, the authors propose a novel convex relaxation for the exponential model, using power cones, that is intersected next with a well-known semi-definite relaxation of unbalanced OPF. To prove the exactness of the method, results are compared to those obtained by the NLP AC OPF formulation. The algorithm proposed in [127] is based on relaxing the NLP equations as conic constraints together with directional, which achieves optimal and feasible solutions over multiple iterations of a SOCP problem.

4.2 Linearisation

Linarised OPF formulations are another commonly used approach that eases the complexity of NLP formulations. It is oriented on linearising equations and constraints, i.e., there are no quadratic or nonlinear equations considering the multiplication of multiple variables.

DC OPF is a linearised model used in transmission network planning and operation and is one of the most exploited linearised OPF formulations due to the simplicity of its implementation [128]. The approximations in the DC OPF formulation include neglecting line resistance and considering only reactance, voltage magnitude of 1.0 p.u. in all nodes, and a small difference between voltage angles of nodes connected by a line. These assumptions are not valid in distribution networks due to differences in the network's configuration and the local characteristic of voltage, which significantly changes based on its electrical distance from the beginning of the feeder. However, there are other linearisation approaches that are often used in distribution network analyses.

Relaxation approaches can be enhanced by linearisation to improve the accuracy or decrease the complexity of AC OPF formulations. The SDP relaxation of the chance-constrained AC OPF is enhanced by introducing new parameters that successfully resolve the issues caused by linear approximations [129]. Gholami *et al.* provide a new method to come closer to the global optimum of SOCP relaxation of AC OPF [130]. The method is based on introducing a new linear transformation that ensures robust precision and higher efficiency while consuming less computing time. The additional complexity of distribution network optimisation is introduced with the penetration of DERs. To tackle the potential computational issues, a QCQP formulation using a linear approximation of the algebraic power-flow equations is presented in [131]. QCQP formulation is then simplified to a linearly constrained formulation, whose benefits are shown with simulation results that utilise realistic PV-generation and load-profile data for illustrative distribution-system test feeders. A lot of optimisation problems require the introduction of binary variables that uplift the existing formulation to mixed integer (MI) and make it even computationally harder to solve. In their paper, Ferreira *et al.* propose a MILP formulation of the AC OPF problem [132]. The presented formulation allows the representation of discrete decisions using integer decision variables, captures the nonlinearities of a distribution network using approximations of controllable accuracy, and can be solved to global optimality with commercial optimization solvers.

The problems with scalability and tractability of AC OPF formulations in distribution networks are even more emphasized in unbalanced distribution networks due to the need to observe all three phases and other characteristics specific to unbalanced networks. Gan and Low present a linearised multi-phase OPF formulation and compare it to two formulations using the SDP relaxations [133]. Case studies show that the linear approximation obtains voltages within 0.0016 per unit of their true values for multiple tested unbalanced distribution networks. Further simplification of the unbalanced OPF formulation is presented in [134]. The proposed approach is able to reduce the computational time needed for solving the problem without the loss of accuracy when compared to other similar approaches found in the literature. However, the results show that the linearisation tends to overestimate voltage rise due to generation and underestimate voltage drop due to load, leading to too conservative or optimistic dispatch results. Another linearisation AC OPF method that accurately calculates the values of voltage magnitude is presented by Huang *et al.* [135]. The presented linearisation can be applied in meshed and radial multi-phase distribution networks, with the dominant quality of solution caused by arbitrary linearisation point, compared to a popular method when linearisation is around the zero injection point. The authors of the paper [136] provide a novel MILP formulation of the AC OPF formulation based on the approximation of the Euclidean form, which is used in the calculation of nodal voltage and branch current magnitudes. The comparison of the linearised algorithm's accuracy, optimality, feasibility, and scalability shows that the proposed formulation is computationally more efficient while being as accurate and more conservative than the benchmarked approaches with maximum errors lower than 0.1%. Linearisation approaches often include neglecting technical constraints that lead to the loss of accuracy. One of the often neglected constraints is the voltage unbalance factor constraint. To show the importance of including the VUF constraint, Vanin *et al.* [137] compare linearised AC OPF and SOCP relaxation with the NLP formulation for different LV network problems. The results show that the level of unbalance in an LV distribution network significantly contributes to the loss of accuracy and the computational burden. In their proposed linearised AC OPF formulation, Grigoudar and Roald present three linearised formulations that do not neglect the voltage unbalance constraint to reduce the computational complexity. Three linearisation methods based on first-order Taylor expansion, fixed-point equation and forward-backwards sweep, can either directly replace the AC power flow constraints for an approximate solution or be incorporated in an iterative, successive approximation scheme to converge to AC feasible solutions [138].

4.3 Optimal Power Flow Solved by Machine Learning

Even though distribution network problems solved by different OPF formulations are traditionally optimisation problems, machine learning (ML) algorithms have recently been more used in solving OPF problems due to their ability to handle complex systems and large numbers of data. Singh *et al.* use sensitivity-informed deep neural networks to match the OPF solutions [139]. The proposed approach is compared to the QCQP OPF formulation and SDP relaxation. The results show the accuracy of the proposed ML approach and the advantage in the computational speed. Moreover, the neural network can be used to improve convergence and accuracy by enabling a warm start in conventional OPF formulations. Another application of artificial neural networks in solving OPF problems is presented in [140]. Reinforcement learning used in training the model avoids the need for reference OPF and enables the integration of discrete decision variables, such as discrete transformer tap changer position in constrained optimisation. Testing of the proposed approach shows high approximation quality and computational efficiency. Neural networks are used for approximating the nonlinear OPF equations in the unit commitment problem by applying the technique that can represent the power flow equations with a sufficiently high degree of accuracy while still maintaining a tractable number of binary variables [141]. The results show that the neural network model outperforms both the DC and linearised power flow approximations when embedded in the unit commitment problem. ML algorithms can also be used to iteratively approach the optimal solution [142]. Once the proposed method comes close to convergence, power flow equations are solved to obtain an overall AC-feasible solution. Falconer and Mones noticed a lack of ML-based approaches that also observe the grid topology information. Several shortcomings in using ML algorithms, including the approaches that have only partially considered the high number of physical models available during training and have offered no guarantees about potential constraint violations of their output, have been identified by Nellikkath and Chatzivasileiadis, who demonstrate how physics-informed neural networks achieve higher accuracy and lower constraint violations, and show how the worst-case violations can be further reduced[143].

Solving three-phase OPF problems using ML algorithms has still not been properly addressed in the literature however, there are several papers that find the correlation between nodal power and voltage magnitude and estimate the potential voltage change with the change in power. One such approach is presented by Bassi *et al.*, who propose the neural network-based approach that neglects the LV network topology and finds the correlation between the values of active and reactive power and voltage magnitude [144]. The results conclude the accuracy of the proposed method, even in the case of the PV integration, which can cause an increase in voltage and reverse power flows. Despite the efficiency of the approach, it neglects several important constraints, such as line ampacity and voltage unbalance, that potentially prevent DSOs from using this approach in some LV network analyses.

4.4 Nonlinear Formulation

As mentioned before, relaxation, linearisation, and ML approaches in solving AC OPF problems contribute to the improvement of the problem's scalability and tractability and the computational efficiency, i.e., a decrease in both computational burden and computational time needed to solve the given problem. All of the mentioned problems exist when using the non-convex nonlinear OPF formulation. Moreover, using a non-convex formulation causes the risk of finding a solution that is only a local and not global optimum. However, the NLP AC OPF formulation is the earliest formulation since it fits within the framework defined by the physical models and laws of the power system [145]. Furthermore, it is the only formulation that guarantees the optimal solution and does not lead to the loss of accuracy, which is an important characteristic in some distribution network analyses.

Geth *et al.* developed the nonlinear current-voltage formulation of the three-phase OPF model, where equations are presented in current and voltage phasors, but also as their real-value equivalents in rectangular coordinates [146]. An OPF implementation is made available as a part of toolboxes developed using the Julia programming language. Another paper focused on the implementation of the unbalanced OPF model is presented in [147], where authors use real-value power-voltage formulation for both bus injection and branch flow models. The paper additionally discusses challenges caused by nonlinearity in implementing the formulation in optimisation modelling toolboxes. In [148], Rigoni and Keane developed and presented Open-DSOPF, an open-source optimal power flow formulation integrated with OpenDSS. The authors used OpenDSS to create a model of a network and modelled unbalanced nonlinear OPF constraints in current-voltage formulation using the Pyomo optimisation framework. The verification shows the accuracy of the proposed tool, which can be used in analyses of active distribution networks. A similar approach is presented in [149], where pandapower is used instead of OpenDSS to create a model of a network. Moreover, both power-voltage and current-voltage formulations are implemented in the optimisation toolbox. After the successful verification, the functionality of the tool is shown in the example of calculating the PV hosting capacity in an LV network. The risk of higher-order harmonics caused by inverters and nonlinear loads requires the extension of OPF models with harmonic constraints. The harmonic OPF (HOPF) model developed using the rectangular current-voltage formulations and solved as a continuous nonlinear optimisation problem is described in [150]. Other than presenting the mathematical formulation of the HOPF problem, the authors describe a three-phase transformer model considering the effects of configuration and saturation and define two case studies used to verify the accuracy and functionality of the proposed approach. However, the proposed approach is not applicable in unbalanced distribution networks, which are becoming harmonic polluters, and there is still a need for HOPF models that can be used in three-phase networks.

4.5 Three-phase Optimal Power Flow Extended With Harmonic and Unbalance Constraints

This chapter of the thesis presents the nonlinear nonconvex current-voltage OPF formulation extended with harmonic and unbalance constraints. The continuous increase in the share of single-phase DERs that are power electronics interfaced to a network emphasizes the importance of such formulation. Besides the set of general constraints and equations, the presented model contains an additional set of equations ensuring the possibility of violating constraints in 5% of observed time intervals, as defined in the relevant standards. However, this requires the use of binary variables that uplift the formulation of the problem to MINLP, which additionally increases the complexity of the given problem. To handle the scalability issues caused by introducing binary variables, an approach that eliminates them, but still allows violating the constraints in some periods is presented.

4.5.1 General Constraints

The first step in developing and implementing the three-phase HOPF formulation is creating the three-phase harmonic impedance matrix (4.1). As mentioned in Section 2.3, there are different methods for creating the three-phase impedance matrix at the fundamental frequency. No matter the chosen, approach, calculating the three-phase impedance matrix for each harmonic order h remains the same, where the impedance of lines and cables are calculated with (4.2) and of transformers with (4.3).

$$\left[Z_{h,ij}\right] = \begin{bmatrix} Z_{h,ij,aa} & Z_{h,ij,ab} & Z_{h,ij,ac} \\ Z_{h,ij,ba} & Z_{h,ij,bb} & Z_{h,ij,bc} \\ Z_{h,ij,ca} & Z_{h,ij,cb} & Z_{h,ij,cc} \end{bmatrix} \tag{4.1}$$

$$\begin{gathered}\left[Z_{h,ij,pq}\right] = \left[R_{h,ij,pq} + j \cdot X_{h,ij,pq}\right] = \\ \left[R_{h=1,ij,pq} + j \cdot h \cdot X_{h=1,ij,pq}\right]\end{gathered} \tag{4.2}$$

$$\begin{gathered}\left[Z_{h,ij\ tr}\right] = \left[R_{h,ij} + j \cdot X_{h,ij}\right] = \\ \left[\sqrt{h} \cdot (R_{h=1,ij} + j \cdot X_{h=1,ij})\right]\end{gathered} \tag{4.3}$$

The common expression for calculating the phase voltage vector in every node of the observed distribution network remains the same at every harmonic order and is represented with

(4.4). Since all values in the OPF model are complex values, they can be represented in rectangular or polar form. In the case of the rectangular formulation, real and imaginary parts of every harmonic voltage are calculated using (4.5)-(4.6).

$$\left[U_{h,j,t}\right] = \left[U_{h,j,t}\right] - \left[Z_{h,ij}\right] \cdot \left[I_{h,ij,t}\right] \tag{4.4}$$

$$\begin{aligned} U^{re}_{h,j,p,t} = U^{re}_{h,i,p,t} - &\sum_{q\in\{a,b,c\}} R_{h,ij,pq} \cdot I^{re}_{h,ij,q,t} \\ + \sum_{q\in\{a,b,c\}} X_{h,ij,pq} \cdot I^{im}_{h,ij,q,t} \end{aligned} \tag{4.5}$$

$$\begin{aligned} U^{im}_{h,j,p,t} = U^{im}_{h,i,p,t} - &\sum_{q\in\{a,b,c\}} R_{h,ij,pq} \cdot I^{im}_{h,ij,q,t} \\ - \sum_{q\in\{a,b,c\}} X_{h,ij,pq} \cdot I^{re}_{h,ij,q} \end{aligned} \tag{4.6}$$

Values of active and reactive power of loads d and generators g in a network are either defined as a known parameter or calculated as a variable, depending on the given optimisation problem. No matter the problem, they are always used to determine the values of the real and imaginary part of the fundamental frequency current, as defined with (4.7)-(4.10).

$$P_{h=1,d,i,p,t} = U^{re}_{h=1,i,p,t} \cdot I^{re}_{h=1,d,i,p,t} + U^{im}_{h=1,i,p,t} \cdot I^{im}_{h=1,d,i,p,t} \tag{4.7}$$

$$Q_{h=1,d,i,p,t} = U^{im}_{h=1,i,p,t} \cdot I^{re}_{h=1,d,i,p,t} - U^{re}_{h=1,i,p,t} \cdot I^{im}_{h=1,d,i,p,t} \tag{4.8}$$

$$P_{h=1,g,i,p,t} = U^{re}_{h=1,i,p,t} \cdot I^{re}_{h=1,g,i,p,t} + U^{im}_{h=1,i,p,t} \cdot I^{im}_{h=1,g,i,p,t} \tag{4.9}$$

$$Q_{h=1,g,i,p,t} = U^{im}_{h=1,i,p,t} \cdot I^{re}_{h=1,g,i,p,t} - U^{re}_{h=1,i,p,t} \cdot I^{im}_{h=1,g,i,p,t} \tag{4.10}$$

Since the previous set of equations enables the calculation of fundamental frequency current, it can be used in calculating the values of higher-order harmonic currents. In most cases, currents at higher frequencies are defined with the share at that frequency in the fundamental frequency magnitude and the angle at the same frequency. Following, higher order harmonic currents are calculated using (4.11)-(4.13). It is important to emphasize that the value of the angle $\phi_{h,d/g,n,p,s}$ changes depending on the phase and the harmonic order according to equations (4.14)-(4.16).

$$I_{h,d/g,n,p,t} = I_{h=1,n,p,t} \cdot i_{h,d/g,n,p,t} \angle \phi_{h,d/g,n,p} \tag{4.11}$$

$$\begin{aligned} I^{re}_{h,d/g,n,p,t} = I^{re}_{h=1,n,p,s,t} \cdot [i_{h,d/g,n,p,t} \cdot \cos\phi_{h,d/g,n,p}] + \\ I^{im}_{h=1,n,p,t} \cdot [i_{h,d/g,n,p,t} \cdot \sin\phi_{h,d/g,n,p}] \end{aligned} \tag{4.12}$$

$$\begin{aligned} I^{im}_{h,d/g,n,p,t} = I^{im}_{h=1,n,p,t} \cdot (i_{h,d/g,n,p,t} \cdot \cos\phi_{h,d/g,n,p}) + \\ I^{re}_{h=1,n,p,t} \cdot (i_{h,d/g,n,p,t} \cdot \sin\phi_{h,d/g,n,p}) \end{aligned} \tag{4.13}$$

$$\phi_{h,d/g,n,a,t} = \angle(h \cdot \theta_{h,d/g,n,a,s,t}) \quad ,\forall h \tag{4.14}$$

$$\phi_{n,d/g,b,s,h,t} = \begin{cases} h \cdot \theta_{h,d/g,n,b,s,t} & , h = 3 \cdot m \\ h \cdot \theta_{h,d/g,n,b,s,t} + 240^{\circ} & , h = 3 \cdot m + 1 \\ h \cdot \theta_{h,d/g,n,b,s,t} + 120^{\circ} & , \ h = 3 \cdot m + 2 \end{cases} \tag{4.15}$$

$$\phi_{n,c,s,h} = \begin{cases} h \cdot \theta_{h,n,c,s,t} & , h = 3 \cdot m \\ h \cdot \theta_{h,n,c,s,t} + 120^{\circ} & , h = 3 \cdot m + 1 \\ h \cdot \theta_{h,n,c,s,t} + 240^{\circ} & , \ h = 3 \cdot m + 2 \end{cases} \tag{4.16}$$

Finally, in order to ensure that the sum of currents going into the node j is equal to the total current going out of the node j, Kirchoff's Current Law (KCL) for the real and imaginary part of the harmonic current at fundamental and non-fundamental frequencies is introduced with (4.17).

$$I^{re/im}_{h,j,p,t\ gen} + I^{re/im}_{h,i\to j,p,t} = I^{re/im}_{h,j,p,t\ load} + I^{re/im}_{h,j\to k,p,t} \tag{4.17}$$

4.5.2 Power Quality Constraints

The approach of constraining the value of voltage magnitude, defining that it needs to be within the allowed interval, is given with (4.18).

$$(U^{min}_{h=1})^2 \leq (U^{re}_{h=1,n,p,t})^2 + (U^{re}_{h=1,n,p,t})^2 \leq (U^{max}_{h=1})^2 \tag{4.18}$$

VUF is defined as the ratio of magnitudes of negative and positive sequence voltage values and its value needs to be lower than the defined threshold value (4.19). Even though the proposed OPF model relies on the phase values, there is a connection between the three-phase system and the zero, positive, and negative sequence system, as shown in (4.20)-(4.21). Therefore, it is possible to represent the VUF-related constraints using phase voltage variables.

$$\frac{(U^{re}_{h=1,n,seq=2,t})^2 + (U^{im}_{h=1,n,seq=2,t})^2}{(U^{re}_{h=1,n,seq=1,t})^2 + (U^{im}_{h=1,n,seq=1,t})^2} \leq (VUF^{max})^2 \tag{4.19}$$

$$\begin{aligned} (U^{re}_{h=1,n,seq=2,t})^2 + (U^{im}_{h=1,n,seq=2,t})^2 = \\ [U^{re}_{a,n} - \frac{1}{2} \cdot (U^{re}_{b,n} + U^{re}_{c,n}) + \frac{\sqrt{3}}{2} \cdot (U^{im}_{b,n} - U^{im}_{c,n})]^2 + \\ [U^{im}_{a,n} - \frac{1}{2} \cdot (U^{im}_{b,n} + U^{im}_{c,n}) - \frac{\sqrt{3}}{2} \cdot (U^{re}_{b,n} - U^{re}_{c,n})]^2 \end{aligned} \tag{4.20}$$

$$(U^{re}_{h=1,n,seq=q,t})^2 + (U^{im}_{h=1,n,seq=1,t})^2 =$$
$$[U^{re}_{a,n} - \frac{1}{2} \cdot (U^{re}_{b,n} + U^{re}_{c,n}) - \frac{\sqrt{3}}{2} \cdot (U^{im}_{b,n} - U^{im}_{c,n})]^2 + \tag{4.21}$$
$$[U^{im}_{a,n} - \frac{1}{2} \cdot (U^{im}_{b,n} + U^{im}_{c,n}) + \frac{\sqrt{3}}{2} \cdot (U^{re}_{b,n} - U^{re}_{c,n})]^2$$

Both harmonic voltages at every frequency and THD$_u$ are limited by relevant standards. However, depending on the number of harmonic orders observed in the problem, defining the constraint for each order significantly increases the complexity of the problem. Therefore, the only focus is put on limiting the value of THD$_u$ with (4.22).

$$\frac{\sum_{h \in H \setminus \{1\}} \left[(U^{re}_{h,n,p,t})^2 + (U^{re}_{h,n,p,t})^2 \right]}{(U^{re}_{h=1,n,p,t})^2 + (U^{re}_{h=1,n,p,t})^2} \leq (THD^{max})^2 \tag{4.22}$$

4.6 The Extension of Thre-phase Optimal Power Flow Model in the Thesis

Despite the importance of using OPF models, their exact formulations are often complex, non-scalable, and computationally inefficient. Many different approximation approaches have been defined to decrease the computational burden occurring in optimisation problems.

Section 4.1 presents convex relaxation of AC OPF problems, including often-used SOCP and SDP relaxations. Despite the advantages in the computational time and decrease in the complexity of the optimisation problem, shortcomings of the approach include the loss of accuracy and objective functions that do not guarantee the optimality of the solution. However, recent findings make the relaxation approaches more accurate and therefore, usable in the planning and operation of distribution networks.

Another common approach to decrease the complexity of AC OPF formulations is presented in Section 4.2. Linearisation approaches are based on replacing non-linear constraints with linear equations. Potential benefits and shortcomings remain the same as in the case of relaxation approaches. However, there are many attempts to improve the accuracy of such approaches, with some of them shown as very efficient.

The application of ML algorithms has penetrated different aspects of distribution network planning and operation, and as presented in Section 4.3, problems solved by OPF models are not an exception. Even though some findings show the dominance of ML-based approaches in terms of accuracy, their disadvantage is the need for large data sets and a high number of historical measurements, which is not always available.

Despite the scalability and complexity issues, the nonconvex, nonlinear formulation is the only AC OPF formulation that guarantees the accuracy of the solution. Therefore, Section 4.4 presents several cases in which the NLP OPF model is used in solving optimisation problems.

Finally, the most significant contribution of Chapter 4 is presented in Section 4.5. The mathematical model of the three-phase NLP OPF formulation is extended with voltage unbalance and harmonic constraints, which are becoming more important in distribution networks with a high share of DERs.

Chapter 5

Main Scientific Contributions

The thesis is built on the contributions divided into three parts. The first part provides a methodology used in detecting and removing errors in the GIS data representing the elements of an LV distribution network. The second part is oriented towards extending the existing three-phase OPF formulation with voltage unbalance and harmonic constraints and the potential application of the OPF formulation in different challenges in planning and operating distribution networks. The final part gives comprehensive PQ analyses based on several case studies defined for different electricity consumption of end-users and share of DERs and investigation of potential methods utilising physical devices or activating the flexibility potential of end-users in decreasing PQ disturbances in distribution networks.

5.1 Geographic Information System Data in Modelling Low Voltage Distribution Networks

With digitisation and the increase in distribution network observability, GIS data representing elements of LV networks are becoming more available. Together with the measurements collected from advanced metering infrastructure, such data is the prerequisite for modelling and analysing distribution networks. However, GIS data in the initial form often contain errors preventing their direct exploitation. Therefore, it is important to collect a sufficient GIS data set and identify the errors that should be removed. The list of identified errors, together with the methodology explained in detail, is presented in [P_1], [P_9], and [P_{11}]. Detected errors are the continuity of a polyline, unknown beginning and ending node of an LV cable/line, disconnection of an LV cable/line and an MV/LV substation or LV switch cabinet, unknown technical attributes of an LV cable/line, LV cable/line without known ending node, and redundancy of point objects. The processing of GIS data was conducted relying on open source technologies, Python programming language, PostgreSQL database system together with the PostGIS extension, and QGIS. The mentioned technologies are the basis for the integrated tool developed for editing GIS data representing LV distribution networks. The main advantage of the open source technologies-based tool is the less complex addition of new functionalities and connection to other databases, e.g., a database containing smart meter electricity consumption measurements. After the GIS data is free of all errors, it can be used in creating the mathematical model of an LV network used in different simulations and analyses of power systems. One of the approaches to creating the mathematical representation of a network is directly using power system simulation tools, which based on technical attributes, create nodes, impedance matrices, loads, and other elements needed for power system analyses. Besides the detailed methodology described in [P_1], [P_9], and [P_{11}], these papers additionally give information related to the connection of GIS data with pandapower, which is then used in distribution network analyses. Additionally, edited GIS data is applied in creating a mathematical model of a network and running distribution network analyses as shown in [P_2] and [P_8].

5.2 Activating End-users Flexibility in Mitigating Power Quality Disturbances

Power quality disturbances potentially have a negative impact on the operation of distribution networks, including the increase in network losses, unwanted and unnecessary tripping of protection devices, and the premature failure of the equipment. Therefore, the need for analysing and afterwards mitigating PQ disturbances is recognised in this thesis. Paper [P_4] presents the results of the real-world study related to the potential deterioration of voltage magnitude and VUF in the case of uncoordinated integration of PVs, EVs, and battery storage. The PQ analysis is extended to harmonic analyses in [P_2], [P_8], and [P_{11}]. Since the results of investigating PQ disturbances show that they are almost inevitable in the case of uncoordinated DER integration, it is important to mitigate them or limit their propagation in a network. There are two identified types of solutions, with the first one oriented towards utilising physical devices and the second one activating the flexibility potential of end-users. There are many device-based methods for improving power quality. Some of them are presented in [P_2], [P_8], and [P_{11}]. However, such methods are often costly, requiring high investments and require often complex reconfiguration of the equipment. Participation of end-users in the improvement of PQ indicators can also be achieved by utilising devices, e.g., three-phase inverters used for the balanced connection of a residential PV system as shown in [P_4] or balancing consumption between the phases as shown in [P_2]. One can say that such solutions also exploit end-users' flexibility since they change on-site consumption or generation to some extent. However, such solutions do not change the total input or output power and just reshape it to be more favourable in decreasing PQ deterioration. Traditional flexibility solutions require the increase or decrease of consumption or generation or their shift in time. Therefore, the demand time-shifting algorithm, aimed at flattening the consumption curve and decreasing the highest (VUF and THD_u) or lowest (voltage magnitude) PQ indicator values, is presented in [P_1].

5.3 Three-phase Optimal Power Flow Formulation Extended with Voltage Unbalance and Harmonic Constraints

OPF models are one of the most used and important models for successful planning and operating distribution networks with a high share of DERs. Formulations and approaches used in traditional power systems are no longer valid since distribution, especially LV networks, require more detailed and precise network models, considering all three phases. Also, DERs are often single-phase connected and have a power electronics interface to a grid, creating a need for extending the constraints in commonly used three-phase OPF formulations. As the first step in filling the research gap, a detailed explanation of the balanced and unbalanced harmonic power flow mathematical model and its implementation using some of the pandapower functionalities, but also creating new ones, relevant in analysing harmonic distortion in distribution networks, is presented in [P_3]. A further upgrade of pandapower functionalities is shown in [P_6], which presents the implementation of power-voltage and current-voltage formulations, their verification and testing on a real-world distribution network planning problem. Further application of the implemented three-phase OPF model in other planning, but also operation problems, is presented in [P_5], [P_7], and [P_{12}]. The need for studying the impact of DERs on the potential PQ disturbances is recognised in this thesis. Besides common node voltage and line current constraints, the OPF model in all mentioned papers also considers the voltage unbalance constraint. However, research conducted in the area often neglects higher-order harmonic constraints. To overcome the gap, [P_{10}] presents the OPF formulation extended with the THD_u constraint applied in calculating import and export dynamic operating envelopes. Since the mentioned paper is more oriented on the application than the model itself, a detailed description of all constraints and equations, with the following explanations, is part of this thesis, presented in Section 4.5.

Chapter 6

List of Publications

Relevant publications divided into journal papers and conference papers cover the main contributions to the thesis and present the method for detecting and removing errors in the GIS data used in the modelling of an LV network, detailed PQ analyses in distribution networks with a high share of DERs, methods for the improvement of PQ indicators values, implementation of three-phase OPF models extended with harmonic and unbalance constraints and their application in planning and operation of distribution networks. Other published papers are not included in the list, even though they are related to the planning and operation of distribution networks and their modelling. However, the main findings of these papers are not closely related to the topic of the thesis, but the interested reader can find them under the author's biography chapter.

6.1 Journal Papers

[P_1]T. Antić and T. Capuder, "A geographic information system-based modelling, analysing and visualising of low voltage networks: The potential of demand time-shifting in the power quality improvement," Applied Energy, vol. 353, p. 122056, 2024 doi: 10.1016/j.apenergy.2023.122056

[P_2]T. Antić and T. Capuder, "Utilization of physical devices for the improvement of power quality indicators during the COVID-19 pandemic and uncoordinated integration of low carbon units," Sustainable Energy, Grids and Networks, vol. 32, p. 100926, 2022 doi: 10.1016/j.segan.2022.100926

[P_3]T. Antić, L. Thurner, T. Capuder, and I. Pavić, "Modeling and open source implementation of balanced and unbalanced harmonic analysis in radial distribution networks," Electric Power Systems Research, vol. 209, p. 107935, 2022, 10.1016/j.epsr.2022.107935

[P_4]T. Antić, T. Capuder, and M. Bolfek, "A Comprehensive Analysis of the Voltage Unbalance Factor in PV and EV Rich Non-Synthetic Low Voltage Distribution Networks," Energies, vol. 14, no. 1, p. 117, Dec. 2020, doi: 10.3390/en14010117

6.2 International Conference Papers

[P_5]T.Antić, A.Nouri, A. Keane, and T. Capuder, "Solving Scalability Issues in Calculating PV Hosting Capacity in Low Voltage Distribution Networks," *2023 International Conference on Smart Energy Systems and Technologies (SEST)*, Mugla, Turkey, 2023, pp. 1-6, doi: 10.1109/SEST57387.2023.10257450

[P_6]T.Antić, A. Keane, and T. Capuder, "Pp OPF - Pandapower Implementation of Three-phase Optimal Power Flow Model," *2023 IEEE Power & Energy Society General Meeting (PESGM)*, Orlando, FL, USA, 2023, pp. 1-5,
doi: 10.1109/PESGM52003.2023.10252870

[P_7]T. Antić, F. Geth, and T. Capuder, "The Importance of Technical Distribution Network Limits in Dynamic Operating Envelopes," *2023 IEEE Belgrade PowerTech*, Belgrade, Serbia, 2023, pp. 1-6, doi: 10.1109/PowerTech55446.2023.10202795

[P_8]T. Antić and T. Capuder, "Analysis of power quality concerning COVID-19-related anomalies and integration of distributed energy resources," *2022 20th International Conference on Harmonics & Quality of Power (ICHQP)*, Naples, Italy, 2022, pp. 1-6, doi: 10.1109/ICHQP53011.2022.9808683

[P_9]T. Antić and T. Capuder “GIS visualization of COVID-19 impact on PQ indicators in distribution networks: A case study of Croatia,” in *13th International Conference on Applied Energy*, Virtual Event, 2021, doi: 10.46855/energy-proceedings-9766

[P_{10}]T. Antić, F. Geth, T. Capuder, "Calculation of Low Voltage Dynamic Operating Envelopes Considering Harmonic Constraints", preprint submitted in *23rd Power Systems Computation Conference (PSCC)*, Paris, France, 2024

6.3 National Conference Papers

[P_{11}]T. Antić and T. Capuder, "Modeliranje i analiza niskonaponskih mreža temeljene na podatcima prikazanim u geoinformacijskim sustavima (eng. Modelling and analysis of low voltage networks based on data represented in geographic information system)," in *8.(14.) savjetovanje HO CIRED*, 2023, Seget Donji/Trogir, Hrvatska

[P_{12}]T. Antić and T. Capuder, "Razvoj programskih rješenja za modeliranje i analizu naprednih distribucijskih mreža (eng. Development of software solutions for modelling and analysis of smart distribution networks)," in *8.(14.) savjetovanje HO CIRED*, 2023, Seget Donji/Trogir, Hrvatska

Chapter 7

Author's Contribution to the Publications

The contributions of the thesis have been accomplished between 2020 and 2023 at the University of Zagreb Faculty of Electrical Engineering and Computing, Unska 3, HR-10000 Zagreb, Croatia and University College Dublin, Belfield, Dublin 4, Ireland (visiting researcher). The research was conducted under under projects listed below:

- Project Innovative Modelling and Laboratory Tested Solutions for Next Generation of Distribution Networks (IMAGINE), co-funded by the Croatian Science Foundation (HRZZ) and Croatian Distribution System Operator (HEP-Operator distribucijskog sustava d.o.o.) under grant agreement PAR-2018
- Project KK.01.2.1.02.0042 Distribution Grid Optimization (DINGO), funded by the European Union through the European Regional Development Fund Operational programme Competitiveness and Cohesion 2014–2020 of the Republic of Croatia
- Project Interoperable solutions for implementing holistic FLEXIbility services in the distribution GRID (FLEXIGRID) funded from the European Union's Horizon 2020 research and innovation programme under grant agreement No 864579
- Project Advanced Tools Towards cost-efficient decarbonisation of future reliable Energy SysTems (ATTEST), from the European Union's Horizon 2020 research and innovation programme under grant agreement No 864298

The author's main contribution in every paper from the list presented in Chapter 6 is given below:

[P_1] In the published journal paper ***"A geographic information system-based modelling, analysing and visualising of low voltage networks: The potential of demand time-shifting in the power quality improvement"***: literature review, methodology for removing detected errors in the GIS data set representing LV network elements, connection of the processed GIS data with the pandapower power system simulation tool, quasi-static time series analysis of the impact of different periods related to the COVID-19 pandemic on PQ indicators, investigation on the potential of end-users demand time-shifting on the improvement of PQ indicators.

[P_2]In the published journal paper ***"Utilization of physical devices for the improvement of power quality indicators during the COVID-19 pandemic and uncoordinated integration of low carbon units"***: literature review, the definition of case studies, analysis of the impact of the increased end-users electricity consumption and share of DERs on values of voltage magnitude, VUF, THD_u, and network losses, comparison of methods oriented on the utilisation of physical devices and activation of end-users flexibility on the improvement of PQ indicators, network and financial losses in an LV distribution network.

[P_3]In the published journal paper ***"Modeling and open source implementation of balanced and unbalanced harmonic analysis in radial distribution networks"***: literature review, implementation of the balanced and unbalanced harmonic power flow model, verification of the implemented model's accuracy by comparison with commercial power system simulations software.

[P_4]In the published journal paper ***"A Comprehensive Analysis of the Voltage Unbalance Factor in PV and EV Rich Non-Synthetic Low Voltage Distribution Networks"***: literature review, the definition of case study, analysis of voltage magnitude and voltage unbalance in a real-world LV distribution network with a high share of DERs, the study of the impact of three-phase connection of DERs on the decrease in the value of VUF.

[P_5]In the published paper presented at the international conference ***Solving scalability issues in calculating PV hosting capacity in low voltage distribution networks***: application of the three-phase NLP model in the PV hosting capacity problem, investigation of the scalability issues in the MINLP formulation, analysis of the loss of accuracy when the use of binary variables is replaced with another approach guaranteeing the NLP formulation.

[P_6]In the published paper presented at the international conference ***"The Importance of Technical Distribution Network Limits in Dynamic Operating Envelopes"***: literature review, the application of the three-phase NLP OPF formulation in calculating export dynamic operating envelopes, investigation of the importance of different technical constraints on the envelopes calculation.

[P_7]In the published paper presented at the international conference ***"Pp OPF - Pandapower Implementation of Three-phase Optimal Power Flow Model"***: literature review, the implementation of current-voltage and power-voltage three-phase NLP OPF formulations with the included voltage unbalance constraint into the pandapower power system simulation tool, the verification of the implemented model on the example of PV hosting capacity in an LV network.

[P_8]In the published paper presented at the international conference ***"Analysis of power quality concerning COVID-19-related anomalies and integration of distributed energy resources"***: literature review, the definition of case studies, investigation of the propagation of PQ disturbances from an LV to MV distribution network in case of different transformer vector groups.

[P_9]In the published paper presented at the international conference ***"GIS visualization of COVID-19 impact on PQ indicators in distribution networks: A case study of Croatia"***: listing the detected errors in the initial GIS data set representing LV network elements, proposing the method for removing the errors, using edited GIS data in the LV network PQ analysis.

[P_{10}]In the paper submitted for the presentation at the international conference ***Calculation of Low Voltage Dynamic Operating Envelopes Considering Harmonic Constraints***: the extension of the thre-phase NLP OPF model with harmonic constraints, the application of the formulation in the calculation of both export and import dynamic operating envelopes.

[P_{11}]In the published paper presented in the national conference ***"Modeliranje i analiza niskonaponskih mreža temeljene na podatcima prikazanim u geoinformacijskim sustavima (eng. Modelling and analysis of low voltage networks based on data represented in geographic information system)"***: presentation of methodology for GIS data processing, analysis of PQ indicators in case studies considering different COVID-19 periods and different shares of DERs.

[P_{12}]In the published paper presented in the national conference ***"Razvoj programskih rješenja za modeliranje i analizu naprednih distribucijskih mreža (eng. Development of software solutions for modelling and analysis of smart distribution networks)"***: mathematical models of the developed tools with the potential application in the planning and operation of distribution networks with a high share of DERs, verification of the tools, and the presentation of their potential use in real-world challenges.

Chapter 8

Conclusions and Future Work

The main focus and contribution of the thesis are developing tools and methods that can be used by DSOs in solving the problems caused by the continuous increase in the share of DERs and their uncoordinated integration, creating challenges in the planning and operation of distribution networks. The final chapter of the thesis is separated into Section 8.1, giving the main conclusions and Section 8.2, presenting guidelines for future work.

8.1 The Main Conclusions of the Thesis

Traditional distribution networks were not complex to plan and operate due to easily predicted consumption and unidirectional power flow. However, changes resulting from higher DERs penetration increased the complexity of planning and operating, emphasising the role of DSOs in the energy transition. However, challenges are additionally aggravated by the low observability of distribution networks leading to the lack of their mapping and consumption or generation measurements on the needed time scale. Due to the unavailability of real-world network data, but also the need to develop the tools and methods oriented towards occurring planning and operation issues, representative, benchmark network models were used to validate the developed methods. However, using benchmark networks cannot be applied in analysing real-world network conditions, and the conclusions drawn from their use are general and not specific to a certain case study. Digitisation has led to an increase in the use of many information technologies, including GIS, allowing the creation of a database containing geospatial relations between objects and technical information about the distribution network elements. GIS data in the initial form often contain numerous errors preventing DSOs and researchers from using them in needed analyses. In this thesis, the list of identified errors in the data set representing Croatian LV distribution networks, together with the methodology of their removal and integration of processed GIS data within the pandapower simulation tool, is presented.

After the successful removal of all errors and connection of GIS data to a power system simulation software, different distribution network analyses can be conducted. Due to the single-phase DERs with a power electronics interface to a network, PQ disturbances and their negative impact on the network operation are coming into the focus of analyses. This thesis presents the results of several different comprehensive PQ analyses. No matter the defined case study, results show severe disturbances caused by uncoordinated DER integration. However, better planning prior to the DER installation or the implementation of methods for mitigating disturbances in networks with already integrated DERs shows the possibility of improving the PQ deterioration. Two main PQ improvement approaches rely on utilising physical devices and exploiting end-users flexibility. As a part of this thesis, several less complex device-based methods are compared in terms of efficiency, but the main contribution is the development of methods aimed at minimising the disturbances and the potential end-users' discomfort caused by activating the flexibility service.

Algorithms based on the OPF formulations allow optimisation-based analyses and implementation of solutions for safer and more reliable planning and operation of distribution networks without the need to decelerate the penetration of DERs. Exact OPF formulations are nonlinear and nonconvex, which makes them unscalable and intractable, and their solving is computationally inefficient. Therefore, there are many linearisation, approximation, or approaches relying on ML algorithms in solving the given OPF problem. However, all of these approaches lead to the loss of accuracy, and in some cases, the found solution is not guaranteed to be optimal. Nonconvex NLP formulations are the only ones without the loss of accuracy, but they are still missing constraints limiting the impact of PQ indicators to the values defined in the national grid code and relevant standards. The extension of the three-phase current-voltage OPF formulation with voltage unbalance and harmonic constraints, are presented in this thesis. Furthermore, binary variables and an additional set of constraints are introduced into the formulation to allow PQ indicators to be outside the interval of values in 5% of periods, as defined in the relevant standards.

8.2 Future Work

Future work will be oriented towards a further investigation of OPF formulations applied in the planning and operation of LV networks with a high share of DERs. Since these formulations require modelling of all three phases, any extension of the formulation increases the scalability issue and the computational time needed to solve the optimisation problem. Therefore, it is planned to investigate different methods that ease the formulation and how it reflects on the loss of accuracy but also in the decrease of the computational burden. One of the potential ways to decrease scalability issues is using ML algorithms to solve three-phase OPF problems due to the existing gap in that field of research.

Furthermore, OPF formulations can be applied to the improvement of PQ disturbances in distribution networks. It removes the need for pre-calculating and iterative methods that do not guarantee the optimal investment or activation of end-users' flexibility. The benefit of such an approach to solving PQ issues is additionally emphasised in calculating flexibility since minimising end-users' discomfort is a prerequisite for their participation in providing requested services. Moreover, large change in their consumption or generation presents a potential financial loss.

The final future research direction will be focused on answering the question of how to encourage end-users on more flexible electricity consumption. The mentioned direction is especially important in the case of PQ deterioration since it is hard to assess how poor PQ reflects on the finances of end-users. Another linking of the technical and economic aspects of distribution network planning and operation is planned to be achieved by investigating the impact of different structures of network fees on the activation of the network's flexibility.

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Abbreviation

ACAlternate current

DCDirect current

DERDistributed energy resource

DSODistribution System Operator

EVElectric vehicle

GISGeographic information system

HOPFHarmonic optimal power flow

HPHeat pumps

LVLow voltage

MIMixed integer

NLPNon-linear programming

OPFOptimal power flow

PVPhotovoltaic

QCQPquadratically constrained quadratic program

VUFVoltage unbalance factor

Publications

There are, in total, 12 journal and conference papers, either published or under review, that are part of this thesis. Four journal papers are attached to the thesis. Due to the brevity, not all conference papers are part of the thesis, but only those already published and presented or accepted for presentation. One conference paper with the "under review" status and two written in Croatian are omitted from the thesis.

Journal Papers

[P_1] T. Antić and T. Capuder, "A geographic information system-based modelling, analysing and visualising of low voltage networks: The potential of demand time-shifting in the power quality improvement," Applied Energy, vol. 353, p. 122056, 2024
doi: 10.1016/j.apenergy.2023.122056

[P_2] T. Antić and T. Capuder, "Utilization of physical devices for the improvement of power quality indicators during the COVID-19 pandemic and uncoordinated integration of low carbon units," Sustainable Energy, Grids and Networks, vol. 32, p. 100926, 2022
doi: 10.1016/j.segan.2022.100926

[P_3] T. Antić, L. Thurner, T. Capuder, and I. Pavić, "Modeling and open source implementation of balanced and unbalanced harmonic analysis in radial distribution networks," Electric Power Systems Research, vol. 209, p. 107935, 2022, 10.1016/j.epsr.2022.107935

[P_4] T. Antić, T. Capuder, and M. Bolfek, “A Comprehensive Analysis of the Voltage Unbalance Factor in PV and EV Rich Non-Synthetic Low Voltage Distribution Networks,” Energies, vol. 14, no. 1, p. 117, Dec. 2020, doi: 10.3390/en14010117

International Conference Papers

[P_5] T.Antić, A.Nouri, A. Keane, and T. Capuder, "Solving Scalability Issues in Calculating PV Hosting Capacity in Low Voltage Distribution Networks," *2023 International Conference on Smart Energy Systems and Technologies (SEST)*, Mugla, Turkey, 2023, pp. 1-6, doi: 10.1109/SEST57387.2023.10257450

[P_6]T.Anti ć, A. Keane, and T. Capuder, "Pp OPF - Pandapower Implementation of Three-phase Optimal Power Flow Model," *2023 IEEE Power & Energy Society General Meeting (PESGM)*, Orlando, FL, USA, 2023, pp. 1-5,
doi: 10.1109/PESGM52003.2023.10252870

[P_7]T. Anti ć, F. Geth, and T. Capuder, "The Importance of Technical Distribution Network Limits in Dynamic Operating Envelopes," *2023 IEEE Belgrade PowerTech*, Belgrade, Serbia, 2023, pp. 1-6, doi: 10.1109/PowerTech55446.2023.10202795

[P_8]T. Anti ć and T. Capuder, "Analysis of power quality concerning COVID-19-related anomalies and integration of distributed energy resources," *2022 20th International Conference on Harmonics & Quality of Power (ICHQP)*, Naples, Italy, 2022, pp. 1-6, doi: 10.1109/ICHQP53011.2022.9808683

[P_9]T. Anti ć and T. Capuder “GIS visualization of COVID-19 impact on PQ indicators in distribution networks: A case study of Croatia,” in *13th International Conference on Applied Energy*, Virtual Event, 2021, doi: 10.46855/energy-proceedings-9766

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A geographic information system-based modelling, analysing and visualising of low voltage networks: The potential of demand time-shifting in the power quality improvement

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ABSTRACT

The challenges of power quality are an emerging topic for the past couple of years due to massive changes occurring in low voltage distribution networks, being even more emphasised in the years marked by the novel COVID-19 disease affecting people's behaviour and energy crisis increasing the awareness and need of end-users energy independence. Both of these phenomena additionally stress the need for changes in the planning and operation of distribution networks as the traditional consumption patterns of the end-users are significantly different. To overcome these challenges it is necessary to develop tools and methods that will help Distribution System Operators (DSOs). In this paper, we present a geographic information system (GIS)-based tool that, by using open source technologies, identifies and removes errors both in the GIS data, representing a distribution network, and in the consumption data collected from the smart meters. After processing the initial data, a mathematical model of the network is created, and the impact of COVID-19-related scenarios on power quality (PQ) indicators voltage magnitude, voltage unbalance factor (VUF), and total voltage harmonic distortion (THD_u) are calculated using the developed harmonic analysis extension of the pandapower simulation tool. The analyses are run on a real-world low voltage network and real consumption data for different periods reflecting different COVID-19-related periods. The results of simulations are visualised using a GIS tool, and based on the results, time periods that are most affected by the change of end-users characteristial behaviour are detected. The potential of the end-users in the PQ improvement is investigated and an algorithm that shifts consumption to more adequate time periods is implemented. After modifying the consumption curve, power quality analysis is made for newly created scenarios. The results show that the pandemic negatively affect all analysed PQ indicators since the change in the average value of PQ disturbances increased both during the hard and post-lockdown period. The time-shifting of consumption shows significant potential in how the end-users can not only reduce their own energy costs but create power quality benefits by reducing all relevant indicators.

1. Introduction

1.1. Impact of COVID-19 on power systems

Besides the well-known technical challenges caused by the continuous increase of LC technologies share and their uncoordinated installation and operation [1,2], in 2020, 2021, and part of 2022 the COVID-19 pandemic has created numerous changes in the planning and operation of power systems and new challenges for system operators. The analysis of the German and other European power systems showed that the pandemic increased the existing power system's uncertainty despite the kept high level of security. The authors in [3] investigated the impact of COVID-19 on the CO_2 emissions and showed that in 2020 the emissions decreased in the industry, transportation, and construction sector. The authors in [4,5] analyse the impact of the pandemic on electricity markets and market operations and show that both electricity prices and power demand were seriously affected by the reaction to the virus. Results of a detailed analysis of the impact of COVID-19 on the behaviour of end-users show that electricity consumption of residential low voltage (LV) end-users has significantly increased [6,7]. The focus of already published research on the COVID-19 impact on LV distribution networks is mostly on the change in consumption and its correlation with environmental, technical, and market aspects of planning and operation of distribution networks. However, the existing literature does not address the impact of the pandemic on power quality and the changes in people's behaviour in the post-pandemic period and

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if their potential in providing flexibility services changes. To overcome the identified gap, we present a detailed analysis of power quality in the LV distribution network over different pandemic-related periods and observe if it is possible to improve deterioration only by shifting demand with the minimum disruption of end-users' comfort.

1.2. Open-source power system simulations

The use of power system simulation tools developed using different programming languages is continuously increasing. The development of pandapwoer, the Python-based open-source tool for different analyses of steady-state power systems is presented in [8]. The mathematical model and the pandapower-based tool for harmonic analysis in both balanced and unbalanced radial distribution networks were presented in [9]. Another open-source platform for modelling, control, and simulations of local energy systems, OPEN, was described in [10]. MATPOWER, an open-source Matlab-based power system simulation package that provides a high-level set of power flow, optimal power flow (OPF), and other tools targeted towards researchers, educators, and students are described in detail by the authors in [11]. Major benefits of open source tools include the possibility to modify and extend their functionalities and to integrate them with other tools and external databases. Such integration with smart meter measurements and geographic information system data is described in detail in the rest of the paper.

1.3. The power of geographic information systems

Due to the increasing complexity of distribution networks, it becomes insufficient to rely only on power system simulation tools. Such tools must be integrated with other tools, systems, and databases. One of the systems being more used in the planning and operation of smart distribution networks is the geographic information system (GIS), a system that contains both technical and geospatial attributes of distribution networks. The authors in [12] present an integration of QGIS, an open source GIS tool, with OpenDSS, an open source tool for power system simulations. Since GIS is characterised by georeferenced data, other applications of GIS-based tools include determining the PV hosting capacity or finding an optimal location for installing a PV power plant [13,14], developing an optimal design of renewable-powered EV charging stations [15], or visualising the results of power flow calculations [16]. A potential disadvantage of using GIS data in its integration with the power system analysis tool is the high probability of different errors in the initial data set. Those errors often make the data unusable in its initial form and further processing and editing are required [17]. Other than GIS data, data collected from smart meters is often considered the key in different distribution network analyses [18,19] or forecasts [20]. A detailed analysis of the potential use and advantages of smart meters in the planning and operation of smart networks is presented in [21,22]. Unlike the other papers that are mostly focused on the single use of GIS in the planning and operation of power systems, in this paper, GIS is applied in editing data representing LV network elements and visualisation of the results of power system simulations. On top of that, we present a detailed step-by-step guide for detecting and editing specific geospatial errors that prevent the direct use of GIS data.

1.4. Mitigation of power quality issues

To prevent power quality disturbances and other technical problems in distribution networks, it is becoming more important to investigate approaches for mitigating these issues. Solutions can be oriented on the utilisation of physical devices such as inverters that help in the mitigation of harmonic distortion [23,24] or re-phasing switches that mitigate network unbalances [25], the potential of end-users where they can help in the improvement of power quality [26] and in avoiding harmonics [27] under multiple demand response schemes created based on the profiles created in the laboratory environment, or on their combination as described in [28]. Besides observing only the potential of end-users' increase or decrease in electricity demand, the improvement of networks' technical conditions can be achieved by the time-shifting of demand. However, this approach is in most cases applied only on the improvement of one value, e.g., voltage magnitude along the feeder [29]. As seen in the literature review, papers often focus on the improvement of the limited set of technical quantities and solutions are often tested on benchmark networks or in a controlled environment. We propose a demand time-shifting algorithm aimed at the comprehensive improvement of PQ indicators. The mathematical model of the algorithm is tested on real-world data — demand measurements collected from smart meters and real-world LV network topology information.

1.5. Contributions

In this paper, we propose an integrated open source tool used for processing and editing GIS and smart meter data, power quality analyses, and visualising the results of the simulations. QGIS, Python, and SQL are used for processing and editing GIS data, smart meter data is processed using Python and SQL, power quality is analysed using the pandapower tool and its developed harmonic calculations extension, while the results are visualised using QGIS. Additionally, Python is used for the detection of time periods that were most affected by the pandemic-related changes. After the detection, a demand time-shifting algorithm is implemented in order to investigate if it is possible to reduce the PQ deterioration only by using end-users potential and without the investment in the additional physical devices. Power quality analyses in this paper are limited only to voltage magnitude, VUF, and THD since these are the only disturbances that can be calculated using the presented model. Other disturbances cannot be detected by quasi-static time series simulations using pandapower or any other tool with the same set of functionalities and their analysis is out of the scope.

To summarise, based on the literature review and identified research gaps, the proposed contributions of this paper are:

- An integrated open source tool used for editing and processing GIS and smart meters data, creating LV network models, performing power quality analyses, and the visualisation of the simulations results.
- A comprehensive analysis of PQ indicators in the real-world LV network during periods related to realistic end-users consumption pattern changes, i.e. COVID-19-related pre-pandemic, pandemic, and post-pandemic periods. Calculated values are compared to limitations in European standards and the impact of the pandemic on the distortion of power quality is investigated.
- Implementation of the end-users demand time-shifting scheme based on the detection of PQ distorted intervals. The developed methodology reduces values of PQ indicators and in some cases even improves PQ and, unlike the papers that rely only on the possibility of end-users to increase or decrease their consumption when needed, results in the effect of less discomforting and more acceptable time-shifting of end-users' consumption on the PQ improvement.

The rest of the paper is organised as follows: Section2gives an explanation of detected errors in GIS and smart meters data and methods used for removing the errors, while the results of analyses defined for a real-world Croatian case study are defined in Section3. Section4 presents the methodology and the results after the implementation of an algorithm used for the improvement of PQ. Finally, conclusion is presented in Section5.

2. Tool description

Using both GIS and smart meters data presents great potential in the improvement of the planning and operation of smart distribution networks and the increase of the network's observability. The problem with this data is that in a high number of cases it cannot be used in its initial form, which presents an obstacle for Distribution System Operators (DSOs). Also, not all data about distribution networks is stored in one system or database. Therefore it is necessary to develop an integrated tool that enables the communication between several systems and databases, that has the possibility of removing errors and preparing data for further analyses.

In the first step, the open source-based tool presented in this paper is used for editing the data and removing the errors in the initial data set. Features of open source technologies QGIS, Python programming language, and PostgreSQL with the postgis extension, are applied for processing the initial GIS and smart meters data. GIS data contains technical and geospatial information about the Croatian real-world LV network, while smart meters data contains information about the end-users' consumption. The focus in this paper is put on data representing a LV network since the main focus was to investigate the potential of residential end-users in the improvement of technical conditions in distribution networks. In case of observing MV networks, the presented tool can be used for processing the GIS data and in case of identifying new errors it can be updated in order to successfully solve all detected problems.

2.1. GIS data

In the process of identifying the errors in the initial GIS data set, several errors were detected, and afterwards, the data was edited in order to enable using it in the creation of the network's mathematical model:

- Continuity of a polyline
- Unknown beginning and ending node of an LV cable/line
- Disconnection of an LV cable/line and an MV/LV substation
- Disconnection of an LV cable/line and an LV switch cabinet
- Unknown technical attributes of an LV cable/line
- LV cable/line without known ending node
- Redundance of point objects

Each polyline that represent the main line of the observed distribution network feeds additional branches of a distribution network. Main lines and branches are connected at a point object called connection point. Even though main line is topologically connected with branches, without breaking a polyline into smaller parts, i.e., segments, determining the beginning and the ending node of each line will not be possible.Fig. 1 shows an example of dividing a line object into segments, where each colour represents an individual segment created by using the developed tool.

Some point objects, e.g., connection points or points that represent end-users, are located at the beginning or the ending node of a line object, i.e., some point objects are topologically connected with line objects representing an LV line/cable. In those cases, based on the equality of coordinates, the beginning and ending nodes of each line object are determined. This change cannot be visualised since only attributes of a line object are changed in a database so they could be used in the creation of a mathematical model of a network based on the edited GIS data.

Some point objects are not located at the beginning or the end of a line, but still, need to be connected with lines. An example of those objects are points representing MV/LV substations or LV switch cabinets. Depending on which node, the beginning or the ending, of a line is unknown, the distance between the first or last coordinate of a line and a point object representing a substation or an electric switch cabinet is determined, and if it is within the radius defined by a user, the point object is attached as a beginning or ending node of a line.Fig. 2 shows an example of a topological connection of a point object representing a substation with line objects representing lines and cables.

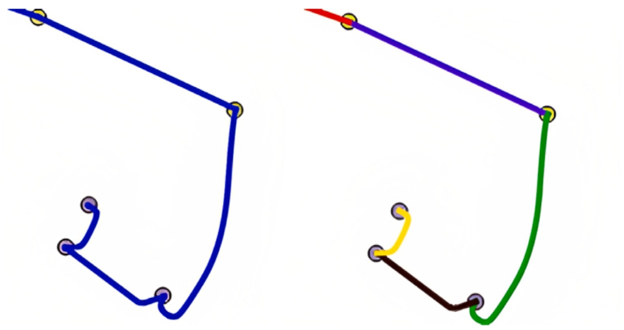


Fig. 1. Dividing a line object into segments.

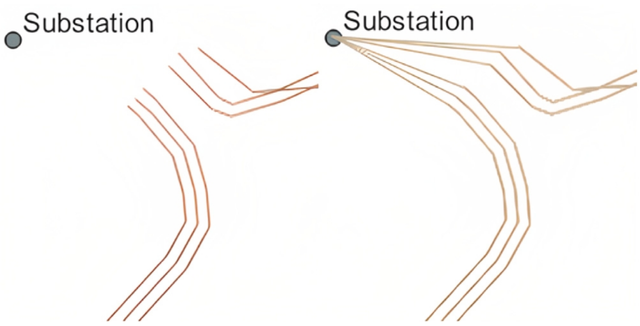


Fig. 2. Connection of a point with line objects.

Fig. 3. Creating a point object.

After all point objects are processed there are still some lines without attached beginning or/and ending nodes. In those cases the missing node is replaced with a point object called a virtual node, which is an element without a connected end-user, i.e., the value of the load at that node is equal to zero. An example of creating a point object representing the virtual node element is shown inFig. 3 .

Some point objects cannot be connected with LV cables/lines since they do not belong to the observed network, i.e., these point objects are not a part of the network and they were input by an accident. Those objects must be deleted from the database and the GIS data set, since they will cause errors in further calculations, e.g., an unbalanced power flow calculation becomes impossible.Fig. 4 shows an example of deletion of an extra node, i.e., of a node representing an end-user that is not connected with the rest of a network.

In the last step of GIS data editing, unknown technical attributes of LV lines/cables are replaced with values for the standard type of a line or a cable that is most common in a database.

Table 1
Example of the smart meter data editing.

	Power (W)						
	Outlier value	Zero value	Missing value		Outlier value	Zero value	Missing value
Time	Initial data			⇒	Edited data		
00:00	575	575	575		575	575	575
00:15	583	583	583		583	583	583
00:30	50000	0	-		583	583	583
00:45	580	580	580		580	580	580

Fig. 4. Deletion of topologically unconnected node.

2.2. Smart meters data

Similar to the error detection in the initial GIS data set, errors are identified in the collected smart meters data:

- outlier values
- zero values
- missing values

Outlier values are defined as the values that significantly differ from the other consumption data, e.g., the consumption of an end-user at one time period is 1000 times larger than in the previous one. In some time periods, the value of consumption is equal to zero. Even though it is possible that consumption lowers at certain periods, there are still several devices in each household that consume energy for basic functions. In some periods, due to a loss of connection between the smart meter and a database or any other obstacle, values of consumption are not stored in the database. Those values are defined as missing ones. All detected errors are resolved in a way that an outlier, zero, or a missing value in a certain period is replaced with the value of consumption in a previous time period. If there are multiple consecutive time periods with some of the detected errors, there is a significant number of intervals in which the initial data cannot be used, or detected errors could not be corrected, the whole consumption data collected from a certain smart meter is neglected. For the purpose of the analysis in this paper, such data is replaced with consumption collected from other smart meters, modified with a randomly determined factor, since it is not expected that two end-users have identical consumption in each time period. An example of the smart meter data editing is shown in Table1 .

2.3. Power quality analysis and visualisation of the results

After all the data is processed and edited and all errors are removed from the initial data sets, prior to calculations it is necessary to merge the data related to the end-users consumption with the GIS data. Since end-users consumption and GIS data are stored in two unrelated databases, the communication between the two systems is established as a part of the developed tool. After the merging of the data, all prerequisites for analyses of LV distribution networks are satisfied.

The second step of the developed tool includes the creation of a mathematical model of an LV network using pandapower, an open source Python-based library for power systems calculation [8]. Additionally, one of the latest pandapower extensions presented in [9] is used for the unbalanced harmonic analysis. LV network elements such as nodes, lines, transformers, and loads (determined by locations of end-users) are created from the edited GIS data, while the value of each load's active power is defined from the smart meter data. Since only active consumption is measured, reactive power of loads is calculated with power factor, randomly chosen from the $[0.95 - 1]$ interval. Once the network with all its elements is created, pandapower is used for time-series simulations and calculation of voltage magnitude, voltage unbalance factor (VUF), and total voltage harmonic distortion (THD_u). Consumption measurements are collected in the 15-min interval over one week and they represent the average value of consumption for every end-user in every 15-min interval. Because of that, calculated values of PQ indicators voltage magnitude, VUF, and THD are also average 15-min values and not values captured at a certain moment. Therefore, the focus of analyses is on the quasi-static time series three-phase harmonic power flow and PQ indicators that are meaningful in the defined time interval. Other indicators such as transients require the installation of additional monitoring devices and cannot be calculated with the used approach and are out of the scope of the paper.

Once the simulations are completed, the results are stored in an external database and used for visualisation using QGIS. In this paper, visualisation is intended to show the change of PQ indicators during the pandemic with respect to the pre-pandemic period, i.e., we investigate and visualise how much did PQ deteriorate or improve due to the changes caused by differences in end-users behaviour during different pandemic-defined scenarios. Results of the scenario that considers the implementation of the consumption time-shifting are also presented, which enables a simple and intuitive assessment of the end-users potential in the general improvement of power quality disturbances.

Tools used in each part of the analyses and the visualisation in this paper, and the developed integrated tool as a whole are presented in Fig.5 .

3. Case study and results

3.1. Case study

An LV network used for the analysis of the impact of different periods related to COVID-19 on the power system is a part of the real-world Croatian distribution network. An urban network consists of an MV/LV transformer, 10 feeders, 179 nodes, from which 139 represent end-users, and 177 overhead lines and underground cables. However, due to the visibility and clarity of the representation of the results, only one LV feeder, with 66 nodes, 43 three-phase and single-phase connected users, and 64 lines, is modelled. The modelled LV feeder is presented inFig. 6 .

Three weeks that represent pre-lockdown, hard lockdown, and post-lockdown periods are chosen to minimise the season's impact on electricity consumption. The first period is set in late winter when the

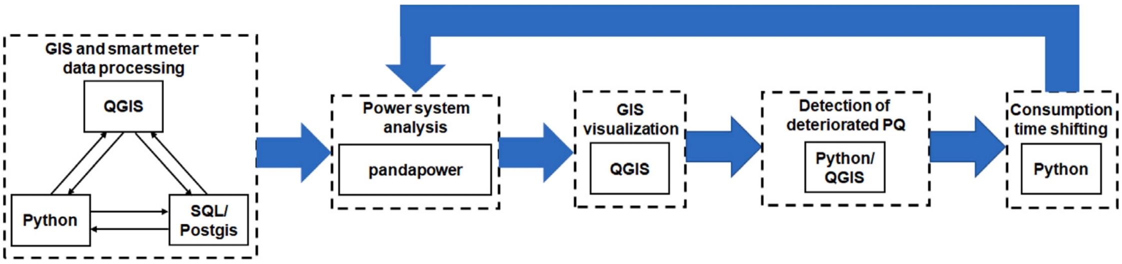


Fig. 5. Integrated tool description.

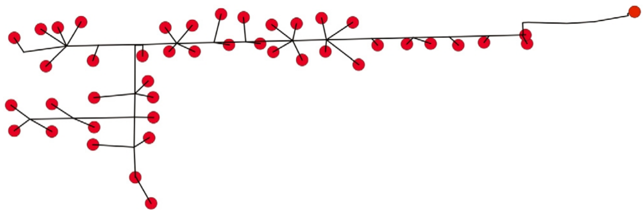


Fig. 6. Modelled LV feeder.

temperatures are not so low, and end-users heat less than in December or January. The second period is set in spring and is characterised by conditions that do not require heating or cooling. Finally, the third period is set in late summer, when the temperatures do not go as high as in July and August, and therefore end-users do not use air conditioners as often as in other summer months. Therefore, consumption and consequentially PQ indicators should not differ so much in the chosen representative weeks. Even more important, consumption during each representative week has captured specific patterns and end-users' behaviour that characterised different periods during the pandemic. Moreover, observation of these specific weeks allows the analysis of the impact of the pandemic on technical conditions in a residential LV network and also presents the opportunity to investigate if some periods were more favourable in terms of the end-users' flexibility provision.

The data from representing weeks presents the cumulative active consumption of end-users connected to an urban LV network, which is converted to the more suitable active power data. The active consumption data is collected in 15-min intervals. Since the smart meters installed in the network defined in the case study do not collect the reactive consumption data, reactive power is calculated from active power and power factor whose value is chosen with uniform randomisation from the $[0.95 - 1.0]$ interval. Together with the data defining the elements of an LV network, this data is used as input into pandapower and its harmonic calculation extension.

3.2. Results

The results of simulations are visualised using the QGIS open source tool. Results show the average change of a PQ indicator during hard (Fig.7) and post-lockdown (Fig.8) periods, compared to the pre-lockdown period. The change is calculated with Eq.(1)where $PQ_{indicator}$ represents the value of voltage magnitude, VUF, or THD_u during each observed COVID-19-related period. Finally, the average change for each PQ indicator in every node is calculated as a mean value of calculated $\Delta_{indicator}$ values in all periods.

$$\Delta_{indicator} = \frac{PQ_{indicator,hard/post} - PQ_{indicator,pre}}{PQ_{indicator,pre}} \tag{1}$$

The defined method of calculating the change considers the pre-lockdown as a referent period that observed end-users' habits before the pandemic. Despite the opening of several business sectors and the relaxation of measures in most of countries during the post-lockdown period, the habits of end-users were changed, e.g., people are working from home more than in the pre-lockdown period. Therefore, the post-lockdown period is also characterised by increased electricity consumption in LV networks. Hence, the change in the value of each PQ indicator is observed with respect to the referent pre-lockdown period. It is important to mention that the change of the value of a certain PQ indicator does not mean that it increased or decreased for the calculated amount, e.g., if the value of THD_u during the hard lockdown period increased to 3% from 2% in the pre-lockdown period, the increase of 50% and not 1% will be visualised using the developed tool. The reason why we focused only on these three PQ indicators in our analyses is the interval in which their values can be calculated. While there are other indicators such as transients, voltage swells or sags, these disturbances are characterised by a short duration or a milliseconds time frame in which they can be detected. There are two main reasons why it is not possible to consider them in analyses — the first being the need for additional measuring equipment since the only available data are the consumption measurements. The second reason is the limitation in terms of possible analyses conducted by the used power system simulation tool. However, other tools used in quasi-static power system simulations share this limitation and make the analyses of dynamic disturbances impossible and not realistic.

3.2.1. Pre-lockdown period

To better evaluate the change of values of PQ indicators during hard and post-lockdown periods, voltage magnitude, VUF, and THD_u are also analysed for the pre-lockdown period in order to calculate values of PQ indicators in the base scenario and determine if there are any violations of defined PQ limitations or if values of observed PQ indicators come close to the threshold values. The minimum value of voltage magnitude is 0.933 p.u., while the maximum is 1.001 p.u. Since most of the European standards and national grid codes define an allowed interval of [0.9-1.1 p.u.] for the value of voltage magnitude, calculated values are not outside the allowed interval in any period during the observed week. However, the minimum value during the pre-lockdown period comes close to the lower bound of the allowed voltage magnitude interval, meaning that any further increase in consumption caused by the pandemic or electrification of heating and transport could cause a violation of defined limitations. The largest VUF value during the pre-lockdown period is equal to 0.539%, which is below the 2% threshold (3% in networks with predominant single-phase connected loads). Even though most of the end-users' devices are single-phase connected to a network none of the devices have power that would create unbalance problems in a network. Single-phase connected devices lead to increased unbalance, but the value of VUF still does not violate the defined limitations. However, installation of any load with large nominal power or a single-phase connected PV will additionally increase the difference between phase consumption and consequentially phase voltages, i.e., voltage unbalance. A similar situation is with THD_u. Even without the integration of LC units that are power electronics interfaced to a network, end-users in LV networks possess a high number of non-linear loads that increase harmonic pollution. The largest value of THD_u in the observed network is 0.886%

which is significantly lower than the maximum allowed value which is equal to 8%. Same as in the case of voltage magnitude and VUF, the increase in consumption and further integration of LC units will only contribute to the harmonic distortion in a network.

3.2.2. Hard lockdown period

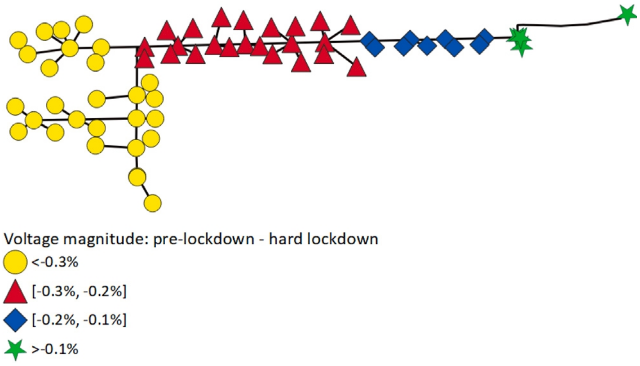
Fig.7(a) presents the average change of voltage magnitude in each node during the hard lockdown period compared to the referent, pre-lockdown period. The results show that the average value of voltage magnitude decreased in all nodes. The decrease is larger than 0.3% at the nodes further from the referent node representing a substation. Voltage magnitude at first several nodes decreased for less than 0.1%, while at all other nodes the decrease is in the range between 0.1% and 0.3%. Even though the value of voltage magnitude is close to the lowest value in the pre-lockdown period, change during the hard-lockdown period does not significantly decrease voltage magnitude. The lowest value is equal to 0.928 p.u., which is negligibly lower compared to the pre-lockdown period. Even though the results show that values of voltage magnitude do not violate the limitations even in the case of enlarged consumption, the decrease presents a concerning trend for DSOs. Since end-users' habits changed during the pandemic, higher consumption is expected in future scenarios and it must be considered in the planning and operation of distribution networks. Also, further and more rapid integration of LC units including heat pumps and EVs will continue the decrease of voltage magnitude and if not prevented, violations of limitations will almost certainly happen.

The change in average VUF value during the hard lockdown period, compared to the pre-lockdown periods is shown inFig. 7(b) . Unlike the average change of voltage magnitude, which was in the range of −0.327% and −0.004%, the change of VUF is significantly larger and is between 64.62% and 106.39%. In most nodes, the average change is lower than 70% or between 70% and 80%, while in several nodes it is larger than 80%. Even though the average change in each node seems very high and concerning, the maximum value of VUF in the hard lockdown period is equal to 0.659%. The results of the analysis show that voltage unbalance increased due to enlarged consumption but it still did not lead to the violation of the threshold value. However, the distribution of consumption among phases is still close to symmetrical, which means that voltage unbalance still does not present a problem for DSOs. Same as with voltage magnitude, an increase of VUF presents a concerning trend which will in the future be more emphasised with the integration of additional single-phase consumption and production units.

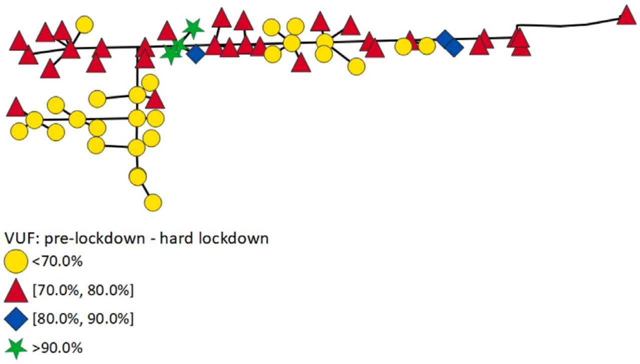
Fig.7(c) shows the impact of increased consumption during the hard lockdown period on harmonic distortion. Even though it is not the only factor in the calculation of THD_u, increased consumption causes higher current at the fundamental frequency and also higher current at higher frequencies since it is defined as the percentage of fundamental frequency current. Such increased current directly increases higher-order harmonic voltages, which together with already shown decreased voltage magnitude at fundamental frequency leads to higher values of THD_u in the observed LV network. Compared to the pre-lockdown period, voltage distortion increased between 12.7% and 14.22% in all nodes, and in more than half of the nodes, the change is larger than 13.5%. However, the largest value of THD_u is 1.027%, which is significantly lower than the 8% threshold value. Despite the maximum value being lower than the limitation, any increase in harmonic distortion caused by higher consumption could present a potential problem for DSOs, since it is expected for consumption to continue to increase in the future, together with the share of power electronics.

3.2.3. Post-lockdown period

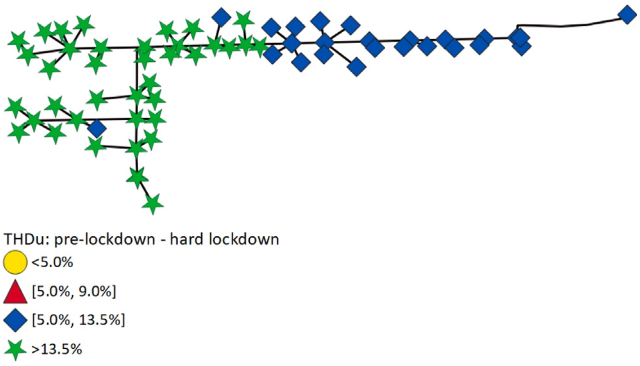
In the post-lockdown period analysed in this paper, most of the government's restrictions were abandoned, however, a significant number of end-users still remained working from home which continued the trend of increased consumption and changes related to PQ in residential LV networks.



(a) Change of voltage magnitude during hard lockdown



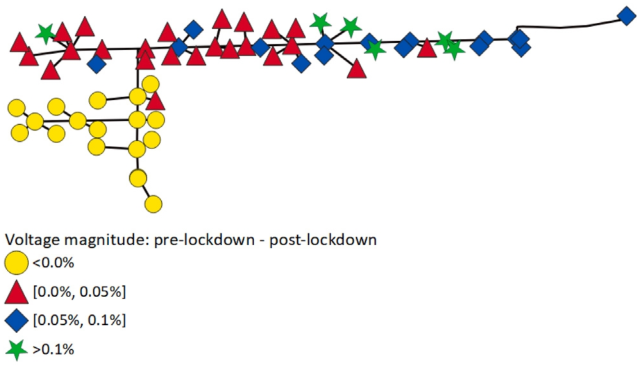
(b) Change of VUF during hard lockdown



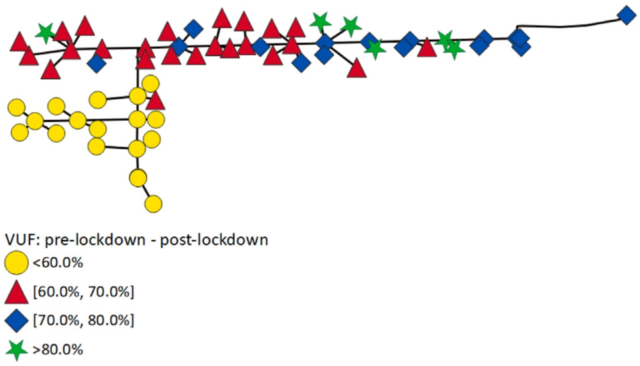
(c) Change of THD during hard lockdown

Fig. 7. Change of PQ indicators during hard lockdown.

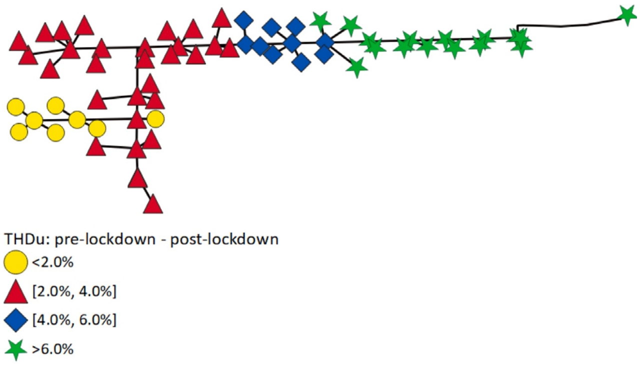
Fig.8(a) shows the change of voltage magnitude during the post-lockdown period, with respect to pre-lockdown. Compared to the hard-lockdown period, the average change of voltage magnitude in this scenario is lower and it even increased in some nodes, with the largest average increase of 0.124%. The largest average decrease of voltage magnitude is −0.048%, meaning that the average value of voltage magnitude is similar to the pre-lockdown period. Also, the minimum voltage magnitude is 0.939 p.u., which is negligibly larger than in the pre-lockdown period. Despite the fact that the behaviour of end-users changed, leading to more often working from home, the post-lockdown period is located in the late summer, almost fall, when consumption is traditionally smaller compared to winter periods, in which the pre-lockdown period is set. The pre-lockdown period is set in late winter when heating is still necessary, especially in continental, more cold parts, where the observed LV network is located. Therefore, the impact of seasonality is more emphasised than the post-pandemic-related



(a) Change of voltage magnitude during post lockdown



(b) Change of VUF during post lockdown



(c) Change of THD_u during post lockdown

Fig. 8. Change of PQ indicators during post lockdown.

changes in end-users' behaviour and the results are more similar to the pre-lockdown than the hard lockdown period.

The change of VUF during post-lockdown is shown inFig. 8(b) . As mentioned before, the connection of large single-phase loads or single-phase connected generation units is more influential on voltage unbalance than seasonality or a scenario related to the pandemic. However, similar to during the hard lockdown period, the results show that there is a higher difference between phase consumption in the post-lockdown period. Compared to the pre-lockdown period, VUF increased in all nodes, but the change that occurs is generally smaller than during the hard lockdown period. The lowest average value of change is equal to 52.64% and the largest to 116.36%. Despite the large change, values of VUF do not violate the 2% limitation in any node and time period, with the largest value of 0.56%.

As mentioned before, the value of THD_u is largely affected by the situation at the fundamental frequency. Even though the results of the voltage magnitude analysis show that there are some nodes in which the average value of voltage magnitude increased, a more detailed analysis of changes in the post-lockdown period shows that there are more time periods with the decrease of voltage magnitude than with increase. Also, the value of THD_u is dependent on more parameters than only on consumption and voltage magnitude at the fundamental frequency. The results inFig. 8(c) show that the average harmonic distortion increased in all nodes in the observed network, with all changes in the range between 1.51% and 7.21%, which are smaller values compared to the changes during the hard lockdown. Also, the maximum value of THD_u is equal to 0.819%, which is lower than the maximum that occurred during the hard lockdown but also during the pre-lockdown period. It is interesting to mention that the trend of the change of THD_u in this scenario is almost identical to the trend of the voltage magnitude change. Nodes with the largest average increase of THD_u are also the nodes with the average decrease of voltage magnitude and those with the lowest increase of THD_u are those with the largest increase of voltage magnitude. The perceived trend additionally brings the value of the average harmonic distortion change into correlation with the average change of current and voltage magnitude at the fundamental frequency.

4. Improvement of the PQ indicators

4.1. Methodology

Even though changes in end-users' habits that arose as a consequence of restrictions during the pandemic have created numerous challenges for DSOs, they also enable potential for a larger exploitation of their flexibility in the planning and operation of distribution networks. In most cases, end-users can help a DSO by increasing or decreasing their consumption or by time-shifting of electricity consumption. Since there are papers that implement a demand-side management scheme and investigate if it is possible to improve the values of different PQ indicators only by increasing and decreasing end-users demand or test the time-shifting approach in a controlled laboratory environment, the focus in this paper is put on the comprehensive improvement of PQ in a real-world LV network only by shifting consumption to other time periods.

In order to avoid unnecessary time-shifting of consumption, happening too often, which will disrupt the comfort of end-users and discourage them from providing such and other similar flexibility services in the future, we developed an algorithm that detects time periods most suitable for time-shifting of consumption. The developed algorithm is a part of an integrated framework presented in this paper. For each day, an algorithm finds 10 time periods in which the change of electricity demand during the hard lockdown period was the largest. The change of electricity demand during hard and post-lockdown is defined with Eq.(2). Even though the trigger for activating the time-shifting service could be set in a different way, e.g., the change of demand was 30% larger compared to pre-lockdown, such definition would lead to too often activation of the time-shifting of consumption service. Therefore, the limitation was set to 10 intervals with the highest value of change for each day.

$$\Delta_{hard/post-pre} = \frac{P_{hard/post,t} - P_{pre,t}}{P_{pre,t}} \tag{2}$$

After all such time periods are detected, the surplus of demand is shifted in eight consecutive time periods (2 h) within 32 periods (8 h) before or after the detected surplus. Time periods in which demand will be shifted are determined as those with the smallest total electricity demand since they will be most adequate for the increase of electricity demand. The step in which the minimum sum is found is defined with Eq.(3).

$$\min \sum_{i=0}^{7} P_{t+i} \qquad \forall t \in [T-32, T-8] \ or \ [T+1, T+24] \tag{3}$$

After the detection of the eight most suitable time periods $[t, t+7]$, the value of the demand increase in each time period $t+i$ is calculated using Eq.(4). Such an approach ensures fair distribution of the total increase of demand among consecutive time periods. An algorithm continuously updates the values of demand, i.e., if there are two consecutive periods detected as the most suitable for time-shifting of consumption, an algorithm will find adequate periods according to updated and not initial demand values.

$$\Delta_{t+i} = \frac{P_{t+j}}{\sum_{j=0}^{7} P_{t+i}} \cdot \frac{(P_{hard/post,t} - P_{pre,t})}{P_{pre,t}}, \quad \forall i \in [0,7] \tag{4}$$

It is important to mention that only active power was observed in the described approach. Reactive power was calculated with the same power factor as in the initial case, before the improvement of the hard lockdown and post-lockdown consumption curves.

4.2. Results

After the implementation of the proposed methodology, the same analyses were made as in Section3.2with the modified, time-shifted consumption curve, which is compared with the results obtained using the pre-lockdown period. The results of that comparison will show if the time-shifting of consumption helped in the PQ improvement or if it did not have any effect and the values remained unchanged.

After the verification of an algorithm used for the detection of time intervals most adequate for time-shifting, more detailed analyses were conducted in order to investigate the effect of time-shifting of consumption on PQ indicators in LV distribution networks. The change of value of the PQ indicators is calculated with respect to the initial value, before the implementation of the demand time-shifting algorithm, using Eq.(5).

$$\Delta_{indicator} = \frac{PQ_{indicator,improved} - PQ_{indicator,initial}}{PQ_{indicator,initial}} \tag{5}$$

Table2shows the result of the change of voltage magnitude, VUF, and THD_u after the implementation of the demand time-shifting algorithm for the hard lockdown period. The results present maximum increase, maximum decrease, average change, and median change for all defined PQ indicators. The maximum increase of voltage magnitude is around 4.5% and the maximum value of voltage magnitude decrease is more than 3%. Even though values of both median and average change are larger than zero, such change of the values that are in the interval between 90% and 100% are not so significant. The time-shifting of demand decreases peak demand and voltage magnitude in some intervals but consequentially increases both demand and voltage magnitude in other periods, causing a so called rebound effect. This effect does not present problems for DSOs since it cannot cause overvoltage or undervoltage, despite the increase in average and median voltage magnitude change. A more detailed analysis of results shows that there are not values close to the upper voltage limitation.

Both VUF and THD_u values are decreased in most periods, which can be seen from the negative median changes of the mentioned values. Same as in the case of voltage magnitude, due to the rebound effect, values of PQ indicators increase in some periods but the value of the increase is around ten times smaller than the increase in case of voltage magnitude. The maximum value of VUF is detected as an outlier value that does not adequately present the potential of the used methodology. Due to this and other similar outliers, the average value of the VUF change is larger than zero. Therefore, using a median value is a better indicator of the improvement of PQ disturbances.

Since the measures related to the COVID-19 pandemic in most countries are seriously relaxed or even completely abandoned, the results related to the improvement of PQ indicators due to demand time-shifting in the hard lockdown period are no longer as relevant as they were a few months or years ago. However, some end-users' habits remain changed even after the hard lockdown and in this paper we test if these habits affect consumption in a way that the improvement of PQ after the implementation of the demand time-shifting algorithm is still possible.

Table 2
Change of PQ indicators during hard lockdown - time-shifted consumption.

	Maximum increase (%)	Maximum decrease (%)	Average change (%)	Median change (%)
Voltage magnitude	4.4458	−3.1886	0.3715	0.2501
VUF	26 446.6319	−99.156	16.9229	−9.5514
THD_u	91.2088	−48.3703	−11.6702	−12.3757

Table 3
Change of PQ indicators during post-lockdown - time-shifted consumption.

	Maximum increase (%)	Maximum decrease (%)	Average change (%)	Median change (%)
Voltage magnitude	2.8399	−2.4235	0.2728	0.1811
VUF	17 230.1585	−99.8613	7.7298	−8.8347
THD_u	76.0736	−46.7923	−9.9796	−10.1633

As it can be seen inTable3, despite relaxing and abandoning the COVID-19-related measures, end-users can still participate in the improvement of PQ indicators. Even though the values of change are smaller when compared to the potential of demand time-shifting in the hard lockdown period, trends of the voltage increase caused by the demand rebound effect, the median decrease VUF and THD_u and outlier maximum value of VUF remain the same as in the hard lockdown period.

Improvement of PQ by implementing demand-shifting algorithm is achieved both in the hard lockdown period but also in more recent post-lockdown period. Although the improvement is less significant for the consumption curve in the post-lockdown period, values of the observed changes show that the implementation of the presented algorithm was not useful only during hard lockdown but even in the case of relaxed and abandoned measures.

There are many other proposed approaches for the improvement of values of PQ indicators, and many of them include the implementation of physical devices such as voltage regulators, phase switching devices, or active and passive harmonic filters. Even though their efficiency is high and they provide the possibility to improve certain technical conditions without compromising the comfort of end-users, their integration in a network often requires investment creating additional and potentially unwanted costs for end-users. Based on the results and the efficiency of the tested approach, the demand time-shifting solution proposed in this paper can be considered as an alternative method for mitigating disturbances in LV distribution networks. However, the proposed method also requires the replacement of the metering equipment, the development of control algorithms, and the installation of equipment needed for receiving and answering signals for decreasing or increasing electricity demand.

5. Conclusion

Together with the rapid integration of LC units, the changes in end-users' habits, such as those exhibited during the pandemic lockdowns, present the biggest challenge in the planning and operation of end-users that the DSOs faced recently. To overcome these challenges, now more than ever, there is an emerging need for the development of tools that can be used both in the short-term and long-term planning but also in the everyday operation of distribution networks affected by the penetration of LC units and long-term changes caused by the pandemic.

One of such tools is presented in this paper, where we rely on functionalities of open source technologies Python, SQL with the postgis extension, and QGIS, and develop a GIS-based framework that is used for processing GIS and smart meters data, creation of an LV network's mathematical model, power quality analyses, and finally, the visualisation of the simulation results. In the first step, several typical errors in GIS and smart meters data are identified and removed using Python and SQL with postgis extension so they can be used in the second step, creating a mathematical model of a network. A mathematical model of a network is created with GIS data containing both technical and geospatial attributes and representing the elements of distribution networks such as substations, lines, or electric switch cabinets. A mathematical model is created with pandapower, the Python-based simulation tool. Pandapower is also used in the third step, where it is used together with the harmonic analysis extension, developed by the authors of this paper, for power quality simulations. PQ indicators voltage magnitude, VUF, and THD_u are calculated and the average change of their value during the hard and post-lockdown periods are compared to the values in the initial, pre-lockdown periods. The final step of the developed tool includes a GIS visualisation with the QIGS open source tool. The results show that on average, all PQ indicators deteriorated during both pandemic periods, with larger disturbances in the hard lockdown period.

According to calculated values, it is possible to conclude that increased consumption during the pandemic presents a potential problem for the DSOs, especially in the networks that are expected to integrate new LC units. To overcome the potential issue, an algorithm that detects time periods most suitable for the shifting of end-users' consumption is implemented as an extension of the presented framework. An algorithm creates a new consumption curve, with minimally discomforting end-users. An implementation of time-shifting of consumption successfully decreased PQ disturbances, with even smaller deterioration of PQ indicators than in the pre-lockdown period.

The results and conclusions presented in the paper are valid for only one analysed LV feeder and they are not relevant to the analysis of all LV distribution networks in the area. However, the main contribution of the developed GIS-based open source tool is the possibility given to a user who can analyse a variety of different feeders or a whole network in order to draw more general conclusions. The feeder in this paper is used as a proof of concept and a test case used for verification of the developed tool. Moreover, the conclusions related to the potential of end-users' flexibility in the PQ improvement are valid no matter the type of network, the only thing that changes is the extent to which end-users can help in mitigating PQ deterioration.

Future work includes further investigation of the potential of using both end-users' flexibility and utilisation of physical devices, how they affect each other's operation, and how they affect the operation costs of DSOs caused by PQ disturbances but also on the finances of end-users considering the incentives for providing different services. The emphasis of future work is planned to be on investigating the economic feasibility of integrating different solutions for the improvement of PQ indicators, including a detailed economic analysis of the ways through which end-users can be financially encouraged to provide services that will lead to a safer and more reliable operation of LV networks.

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CRediT authorship contribution statement

Tomislav Antić: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, visualisation. **Tomislav Capuder:** Conceptualization, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Utilization of physical devices for the improvement of power quality indicators during the COVID-19 pandemic and uncoordinated integration of low carbon units

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ABSTRACT

COVID-19 affected numerous sectors and changed traditional people's behavior. The restrictions led to a decrease in consumption in industrial and business sectors, while electricity consumption in households significantly increased. To determine the correlation between COVID-19 and power quality (PQ), consumption curves relevant for different pandemic periods are used in the analysis of multiple PQ indicators in a real-world low voltage distribution network. The hard lockdown consumption curve is used as the reference for future scenarios with a high share of low carbon (LC) units including PVs, heat pumps, and electric vehicles. Simulations show that COVID-19 negatively impacted technical conditions in distribution networks and different methods based on the utilization of physical devices are tested to mitigate disturbances. We additionally test the potential of implemented methods in the decrease of technical and financial losses. Almost all methods contribute to the decrease of network losses, which is significantly important to Distribution System Operators (DSOs) due to the recent increase in electricity prices. The final contribution of the paper is finding a correlation between the PQ disturbances and financial losses. Results show the impact of the value of voltage unbalance on network losses, while other indicators do not present a significant problem. The results of simulations and drawn conclusions could be used as a guide for DSOs facing the uncoordinated penetration of LC units. Also, setbacks of the implemented method are detected as a first step in the further improvement of technical conditions.

1. Introduction

The COVID-19 pandemic affected numerous sectors and created unexpected challenges for different businesses in the last two years. One of the most affected sectors is the electricity sector, which has faced different changes in the operating segment. Since most of the governments introduced serious restrictions, a lot of people did not go to their offices and instead, they stayed at households and cumulatively, the total electricity consumption decreased during the pandemic [1,2]. Due to restrictions and a different set of measures, the business consumption decreased during the pandemic [3]. On the other hand, the electricity consumption at the low voltage (LV) level and the loading of distribution transformers increased because of the same restrictions, especially during office hours [4,5]. Besides the consumption, the COVID-19 has seriously affected other aspects of the power systems planning and operation; the load forecasting methods need to be improved due to the changes caused by the pandemic [6], electricity markets faced the decrease in prices [7], the deployment of DERs was slowed down [8,9], etc. The authors in [10] provide a comprehensive analysis of the COVID-19 pandemic on the Italian power system, considering the changes in demand and generation, electricity markets, and ancillary service provision but also provide a blockchain-based architecture used in demand response programme as a countermeasure for the problems related to the pandemic. However, none of the papers provide a detailed analysis of the COVID-19 impact on power quality (PQ) and do not observe how the PQ indicators changed during the pandemic. Since the COVID-19 pandemic affected the habits of end-users, it is expected that similar behavior which leads to increased electricity consumption remains in future scenarios. Therefore, the COVID-19 related scenarios are extended with the integration of low carbon (LC) units. Besides the analysis of PQ indicators during different periods in the COVID-19 pandemic and with a different share of LC units in a network, a set of measures based on the utilization of physical devices is investigated in this paper. The utilization will help in the mitigation of problems related to the COVID-19 pandemic but also will enable integration of LC units in distribution, especially, low voltage (LV) networks, in power systems marked with pandemic-related changes.

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Having the electrical energy of satisfactory quality is one of the most important aspects of distribution network planning and operation segments since the deterioration of power quality can lead to unwanted events in power systems [11]. Also, PQ disturbances can lead to direct, indirect, and social-economic impacts including increased network losses, equipment damage, additional loading of components, etc. [12]. The results of the Pan-European PQ survey show that PQ costs in Europe are responsible for serious costs but that most of these costs and installation issues can be avoided with better design and greater investment in the equipment [13]. The authors in [14] analyze the impact of the integration of power electronics in residential distribution networks and find a correlation between PQ disturbances and economic losses. The authors' estimation is that bad power quality in the Brazilian power system can exceed one billion dollars for the 8-years span. Most of the papers analyze the PQ economic of large industrial consumers since the correlation of their PQ with the economic losses is much easier to determine than one of the residential consumers. Also, the determining impact is in most cases based on surveys and not on the proposed methodology and the results of simulations. In this paper, we calculate direct financial costs caused by the increase or decrease of network losses, based on the observed case study and the investigated method for the PQ improvement, which is especially important with the post-covid increase in electricity prices.

Due to mentioned technical and economic problems caused by deteriorated PQ, it is important to monitor and analyze the values of PQ indicators but also to develop and propose methods that will be used in the improvement of PQ, especially in the cases of the violation of limitations defined in the standards and national grid codes. The importance is additionally emphasized with the integration of distributed energy resources. The problem with the integration of DERs is that it is often uncoordinated, i.e., end-users do not consider the negative impact of a random phase to which an LC unit is connected or problems caused by the EVs charging or the electrification of the heating and using the heat pumps [15–17]. Even though the impact of LC units on PQ indicators is already a well-investigated problem and the DSOs are well-aware of their possible negative effect on technical conditions in distribution networks, we contribute to state-of-the-art with the analysis of the impact of LC units on PQ indicators in an LV network already affected by the COVID-19 pandemic, where hard lockdown is defined as the initial scenario, characterized by the increased consumption that is expected in the future. Real-world measurements defining the EVs' charging, consumption of heat pumps, and the production of PVs are normalized and curves that are used over different scenarios are created. Besides the change in the value of LC units' power, different scenarios define the connection phase of each LC unit and the combination of LC units that each end-user has installed. That way, a deterministic approach that is valid only for one specific scenario is avoided and the results of the comprehensive analysis, i.e., analysis of multiple PQ indicators, lead to more general conclusions that be considered during the planning and operation of future distribution networks.

To mitigate or at least decrease negative impacts of poor power quality but also to decrease network losses, numerous methods have been proposed in research papers, theses, and technical reports. The solutions and methods for the PQ improvement could be divided into those oriented to the utilization of physical devices or DSO's assets, e.g., power electronic devices [18] or battery storage system [19], and to those oriented to the exploitation of the end-users potential, e.g., end-users flexibility [20]. Since both approaches have numerous advantages but also disadvantages, their comparison requires a detailed analysis that is outside of the scope of the paper. The focus of this paper will be only on the possibilities of the physical devices, smart inverters and phase-switching devices, that are installed at the locations of end-users. Power electronics (PE) devices, e.g., inverters, have shown great capability in the mitigation of different PQ issues. Volt/Var control of PE devices is often used in regulating the voltage magnitude, and additionally, the method proposed in [21] overcomes the PV imbalance-induced voltage regulation challenge, and consequentially, voltage unbalance challenges. The replacement of distribution lines and cables is another way of decreasing power quality problems and network losses by the investment in the equipment. The authors in [22] provide a technical and economic analysis of the overhead lines replacement with the goal of losses reduction and voltage profiles improvement. A loss reduction by the replacement of distribution lines is also investigated in [23]. Voltage magnitude and especially voltage unbalance problems are often resolved with the installation of low-cost phase switching or phase swapping devices. The authors in [24] propose a novel method that determines optimal PVs re-phasing and successfully avoids voltage unbalance, while simultaneously increasing a PV hosting capacity. A scheme proposed in [25] uses a central controller that transfers residential loads from one phase to another so that voltage unbalance is minimized along the feeder. The authors in [26] determine an optimal location for static switches that are used for the improvement of voltage unbalance. Unlike most papers that observe Volt/Var control of only DERs, e.g., PVs or battery storage, the authors in [27] additionally observe smart inverters and reactive power scheduling of home appliances in the decrease of voltage magnitude and unbalance-related problems. Some inverters and compensators are modeled in a way they create delta and wye connection and therefore, they compensate the neutral and zero sequence currents, similar as distributed transformers with the Dyn vector group [28,29], which is especially beneficial in the mitigation or decrease of harmonic distortion. Unlike the mentioned papers that focus on the improvement of only one PQ indicator or in some cases on two indicators significantly connected, e.g., phase voltage magnitude and voltage unbalance factor, we investigate the efficiency of four different methods in the comprehensive improvement of PQ but also their potential for decrease of network losses. Methods are compared in terms of decreasing the frequency of violation, decreasing the value of the limitations excess, and the reduction of financial losses correlated with active network losses. Since the initial results show that there are no violations of harmonic limitations in a network, the implemented solutions are more oriented toward the improvement of voltage magnitude and voltage unbalance problems but their possibility of decreasing the harmonic pollution is also investigated.

In this paper, we analyze the impact of the changes during different pandemic-related periods on values of PQ indicators: voltage magnitude, voltage unbalance factor (VUF), and total voltage harmonic distortion (THD_u) and on active network looses, the quantity that is not defined as a PQ indicator but which potential increase becomes concerning due to the recent increase in the electricity prices. The expected increase of electricity consumption is represented with the hard lockdown period, characterized with the longer end-users' stay at home and therefore, increased consumption, especially during the working hours. The scenario defined with hard lockdown is used as the basis in analyses of the impact of PVs, EVs, and heat pumps on the deterioration of PQ in a real-world LV residential distribution network. To draw more general conclusions and to overcome uncertainties, a large number of scenarios defining the connection phase of LC units, their nominal power, and other important factors are created and used in simulations. Even though there are solutions oriented toward the exploitation of end-users that show great potential in minimization of power quality issues and network losses, the focus of this paper is on using the physical devices and DSO's assets. Therefore, the exploitation of end-users potential is not analyzed in this paper. In order to meet the requirements of satisfying the PQ limitations in 95% of observed 10-minute intervals during one week, multi-temporal simulations were run and the results were compared with the constraints defined in the relevant European standards. Besides analyzing the frequency of the violation, we compare calculated PQ indicators with the values that could cause serious problems even in the case of violation in only one time period. Increase of cables'/lines' section, phase switching, three-phase connection, and Volt/Var control are introduced as methods for the improvement of PQ. Even though all these methods are already tested and described in detail elsewhere, we provide a comparison of their efficiency in the PQ improvement with respect to both frequency and the value of the constraints violation. Finally, we test the potential of the methods for the improvement of active network losses and that way, we find a correlation between deteriorated PQ and economic losses. To summarize, the following contributions are proposed:

- A comprehensive analysis of power quality indicators and network losses caused by the COVID-19-related changes and the integration of LC units. The impact of DERs' integration is investigated together with the increased consumption measured during the hard lockdown period. Such consumption characterizes future scenarios of enlarged consumption which makes this analysis important for the aspects of planning and operation of distribution networks in the following years. The calculated values are compared to the limitations defined in the European standards, i.e., we analyze if these values satisfy the requirements in more than 95% of observed time periods. Additionally, the results were compared with the additionally enlarged allowed boundaries, i.e., minimum threshold values were decreased and maximum increased, since the violation of the newly proposed threshold values in the only one time period could cause potential problems for a DSO.
- Investigation of the efficiency of four different methods in the potential improvement of power quality. Despite all the methods being already tested, we provide a comparison of their efficiency in terms of the largest comprehensive improvement, i.e., each method is tested for the improvement of all observed PQ indicators. The results and drawn conclusion can be used as guidance for the connection of DERs in LV distribution networks in order to minimize PQ disturbances.
- Finding a correlation between PQ disturbances and direct economic costs caused by increased network losses. There are papers that analyze PQ economics but in most cases, they are oriented on the results of surveys or analyzing the impact of only one indicator. In this paper, we determine potential financial savings when all PQ indicators are improved.

The rest of the paper is organized as follows: definitions and mathematical model used for the calculation of different PQ indicators is presented in Section2. A definition of each case study and the differences between them are presented in Section3. The results of analyses are shown and discussed in Section4. In Section5, the implementation of methods for the improvement of PQ indicators and the decrease of network losses are defined and the results after the utilization of physical devices are presented. Finally, Section6gives the conclusions and directions for future work.

2. Power quality — definitions and mathematical model

As mentioned in Section1, poor power quality can lead to unwanted problems in the planning and operation of smart distribution networks, e.g., increase of technical and economical losses. Therefore, it is important to run simulations, make analyses, and observe the values of PQ indicators. In order to do that, it is important to develop and use tools that are available for comprehensive and more complex analyses of distribution networks. One of such tools is pandapower, a Python-based tool used in this paper. The pandapower tool is used for both unbalanced load flow (LF) analysis and unbalanced harmonic analysis [30,31].

One of the results of the unbalanced LF calculation is the voltage magnitude of each phase and node. Several European standards [32,33] and the national grid code [34] define that the value of voltage magnitude must be between 90% and 110% of nominal voltage magnitude for 95% of 10 min values during one week.

Even though there are different methods that can be used in the calculation of voltage unbalance in distribution networks, the voltage unbalance factor (VUF) in this paper is calculated using Eqs.(1)–(2). Since the result of unbalanced LF is the voltage magnitude of each phase, phase voltages need to be transformed to zero, positive, and negative sequence system values, according to Eq.(1). Afterwards, VUF of each node is calculated as the ratio between negative and positive sequence system values, as defined in Eq.(2).

$$\begin{bmatrix} U_{0,n} \\ U_{1,n} \\ U_{2,n} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} U_{a,n} \\ U_{b,n} \\ U_{c,n} \end{bmatrix} \quad where,\ a = 1\angle 120^\circ \tag{1}$$

$$VUF_n = \frac{U_{2,n}}{U_{1,n}} \cdot 100\%(2)$$

This approach to the VUF calculation is defined in the IEC 61000-2-2 European standard [32]. Besides the mathematical formulation of the VUF calculation, IEC 61000-2-2 together with the EN 50160 standard, [33] define threshold values for voltage unbalance. As defined in these standards, the voltage unbalance factor in LV distribution networks may not exceed 2% for 95% of 10 min values during one week. The exceptions are locations with a high number of single-phase loads where this value is exceeded to 3%. Standards [32,33] define the threshold value for the whole network but they do not present the limitation for LV nodes to which end-users are connected. The value of VUF that is used as the benchmark value in analyses in this paper is defined in Croatian Grid Code for distribution networks [34] and is equal to 0.7%.

Besides phase voltage magnitudes and VUF of each node, pandapower is used for calculating higher-order harmonic voltages and total voltage distortion factor of each phase and node ($THD_{u,p,n}$). Even though the tool used for PQ analyses in this paper is already developed, a harmonic calculations extension is developed by the authors of these papers. The detailed mathematical model of the unbalanced harmonic analysis and its implementation in pandapower is detailed described in [31] and in this paper we test the functionalities of the developed tool on real-world case studies and a large number of scenarios.

Standards [32,33] and Croatian Grid Code [34] define that the value of $THD_{u,p,n}$ should not exceed 8% for 95% of 10 min values during one week. They also formulate the way for the $THD_{u,p,n}$ calculation, defined with Eq.(3).

$$THD_{u,p,n} = \sqrt{\sum_{h=2}^{H} \left(\frac{U_{p,n,h}}{U_{p,1}} \right)^2} \tag{3}$$

Table 1
Threshold values for higher-order harmonic voltages.

h	u_h(%), [32,33]	u_h(%), [34]
3	5.0	3.0
5	6.0	3.0
7	5.0	2.5
9	1.5	1.5
11	3.5	2.5
13	3.0	2.0

Except the threshold for $THD_{u,p,n}$, standards [32,33] and the national grid code [34] define the limitations for values of harmonic voltages at each non-fundamental frequencies. Since in this paper first six higher-order harmonic voltages are calculated, their threshold values are presented inTable1.

The values of each calculated PQ indicator is compared to the above-mentioned values. These values are used in the identification of end-users most affected by the poor power quality, both in the analysis of the COVID-19 impact and the impact of DERs integration.

3. Case studies

As mentioned before, the COVID-19 pandemic changed the behavior of end-users and those changes impacted the operation of distribution networks. To assess these changes, the initial case study is defined for three different COVID-19-related periods. The first period is the pre-lockdown period, defined in February 2020. In Europe, there were no problems related to the pandemic and the consumption of end-users followed the traditional pattern. The second period is the period of a hard lockdown and it is defined in April 2020. During the hard lockdown period, end-users spent most of the day at their homes, since the majority of end-users worked from home due to strict government restrictions. The consumption during the day was larger compared to values in the traditional consumption curve. The final period is the post-lockdown period, defined in June 2020, when most of the strict restrictions were abandoned, end-users started to work at their offices and did not spend so large part of the day at their homes. After defined periods, there were several other soft and hard lockdown periods with a similar consumption pattern as in April 2020. Therefore, further periods are not considered in this paper.

Even though the most strict restrictions are abandoned, the COVID-19 pandemic changed a lot of end-users habits, and a significant number of them still work from home or in hybrid form. Even though the global consumption decreased during the pandemic, it has started to grow in 2021 and 2022, and it is expected that the global consumption soon reaches the pre-pandemic level. The growth will be especially important in residential LV networks, since in the European Union, energy consumption in the buildings is more than 40% of total energy consumption [35]. The end-users in buildings and family houses more often decide to invest in electrification of the heating or the installment of household EV charging stations, their future consumption will only increase and surpass the pre-pandemic levels of consumption. Due to changes in the end-users behavior and traditionally higher electricity consumption, future scenarios can be characterized with electricity consumption specific for the hard-lockdown period.

As mentioned in Section1, the prices of electricity have increased in 2021, together with the prices of energy sources, e.g., gas. Since the gas is often used for heating, end-users will decide to invest in technologies that will decrease their bills at the end of the month. Therefore, it is expected that the share of heat pumps or other similar technologies rises in the future. Also, PVs are becoming more profitable, their price is decreasing faster than it was projected, and the decrease is only expected to continue [36].

Besides the initial analysis in which the impact of the COVID-19 pandemic on PQ indicators and network losses is defined, additional scenarios of the LC units penetration are defined. As mentioned before, consumption during the hard-lockdown period is chosen as the possible future scenario. Further analyses will include different levels of the penetration of PVs and heat pumps. In four case studies, PVs and heat pumps are installed at randomly chosen 20%, 40%, 60%, and 80% of nodes to which end-users are connected.

To summarize, five case studies are created to assess the impact of the COVID-19 pandemic and the integration of LC units on the value of different PQ indicators and network losses. In Case Study 1, three different COVID-19 related periods and their impact on power quality and network losses are analyzed. From Case Study 2 to Case Study 5, electricity consumption characteristic for the hard lockdown period is combined with the LC units that are installed at 20%–80% of LV nodes. The results of Case Study 2-Case Study 5 will show the readiness of DSOs for the technical challenges caused by the increased share of LC units.

A real-world Croatian residential LV network is modeled using pandapower, both for unbalanced load flow and unbalanced harmonic analyses. The modeled network shown inFig.1contains one MV node, an MV/LV transformer, and 140 LV nodes. End-users are connected to 79 of those nodes, while other nodes are auxiliary nodes, e.g., LV switching cabinets or coupling points that are used for the connection of underground cables and overhead lines. LV line objects are modeled with the direct and zero sequence resistance and reactance, length, and maximum allowed current.

Smart meters present great potential in the easier planning and operation of distribution networks. One of the advantages is storing the relevant end-user data that can be used in different power system analyses. Consumption data for the pre-lockdown, hard lockdown and post-lockdown periods are collected and used as input in PQ analyses. The problem occurred since not all the relevant data is accessible, i.e., information about phase consumption and reactive power is not measured and therefore is not available. In order to overcome the problem, we create a large number of scenarios in which consumption is randomly distributed among the phases and reactive power is calculated with the power factor randomly chosen from the interval [0.95–1]. Different scenarios were created in order to better cover a wide range of possible situations that could occur at end-users locations. Despite the randomization, all of the scenarios are created in a realistic way, i.e., the distribution of consumption was done so that the initial unbalance is not too large and the interval from which the power factor was chosen is commonly used in power system analyses.

Depending on the case study, a certain share of end-users is equipped with PVs and heat pumps. The nominal production power of a PV is randomly chosen. If the power is lower than 3.6 kW, PVs are single-phase connected to a randomly selected phase, while in the case of a larger power, PVs are three-phase connected to a network. The PV production curve is created from the data for the location which corresponds to the network used for analyses in this paper [37]. Time-dependent curves for heat pumps are created from the on-site measurements.

The measured values are used in unbalanced load flow simulations, and the results of simulations are used in the analysis of voltage magnitude, voltage unbalance factor, and LV network losses. The rest of the PQ indicators analyzed in this paper are total voltage harmonic distortion (THD_u) and higher-order harmonic voltages. Residential end-users are equipped with

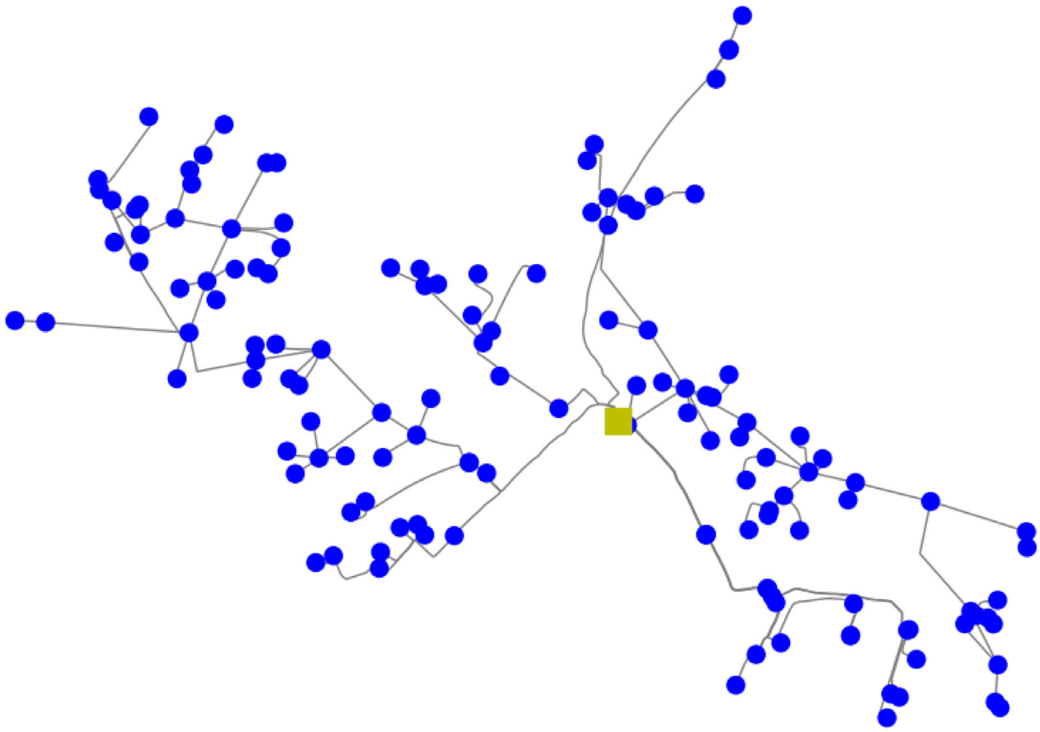

Fig. 1. A residential LV network.

numerous devices that inject higher-order harmonic currents into a network. PVs and heat pumps are connected to a network through power electronic devices and are also significant harmonic polluters. The residential harmonic spectrum used for defining higher-order harmonic currents is created according to [38,39] and PVs harmonic spectrum is created according to [40]. The harmonic spectrum of heat pumps is created from the data presented in [17]. After all input data is defined, an extension of the pandapower library is used for the unbalanced harmonic analysis. The values of PQ indicators are compared to the limitations defined in European standards [32,33].

4. Results

4.1. Impact of the COVID-19 pandemic

As described in Section4, Case Study 1 (CS1) is the initial case study where only the impact of the COVID-19 pandemic on network losses and PQ indicators is investigated. Three different scenarios defined with the energy consumption during pre-lockdown, hard lockdown and post-lockdown periods are created.Fig.2shows values of network losses during one week for each of three defined scenarios.

Since the energy consumption in residential LV networks is significantly correlated with the novel corona virus disease, it is expected that the active network losses change, depending the COVID-19 scenario. As it can be seen fromFig.2, there is a high correlation between active network losses and the COVID-19 pandemic. The results of the analysis show the general increase of network losses during the hard lockdown period. The increase is especially visible during the working hours since most of the end-users stayed and worked from home. This change of behavior led to increased electricity consumption and consequentially increased network losses. Similar values of network losses can be seen during Saturday and Sunday, since no matter the scenario, most of the end-users spend the majority of the day at home. Even during the weekend, there is increased consumption during parts of the day that are usually marked with social activities. There is also an exception, that could be defined as an outlier value, on Thursday when active network losses are largest during the post-lockdown period. In spite of the occurred outlier value, it can be concluded that the COVID-19-caused hard lockdown increased the network losses, which could be problematic for the DSOs in the future, especially due to the recent increase in electricity prices.

The second analyzed quantity was voltage magnitude. Due to the correlation between the demand and voltage magnitude, the effect of the pandemic on voltage magnitude is expected to be significant. Voltages of phases A, B, and C during each of COVID-19-related periods are presented inFig.3.

Observing the values of phase voltages, the magnitude is lowest during the hard lockdown period, which was expected, due to the increased electricity demand. Even though some outlier values in the pre- and post-lockdown period are close to the values during the lockdown period, the largest range of values in the interquartile interval and the lowest median values happen always in the lockdown period. As can be seen infFig.3, all voltage magnitude values are larger than 0.9 p.u., the lowest allowed value defined in the standards. However, during the hard lockdown period, the lowest value of voltage magnitude comes close to 0.92 p.u., which is significantly closer to the lower bound than to the nominal voltage. Further integration of LC units, e.g., heat pumps and EVs, in the LV part of a distribution network could lead to the violation of limitations related to the allowed voltage magnitude.

As the results of the voltage magnitude analysis show, phase voltages are not symmetrical, i.e., there is a certain amount of voltage unbalance in the observed residential network.Fig.4 shows results of voltage unbalance factor (VUF) during pre-lockdown, hard lockdown and post-lockdwon periods.

The results inFig.4show that values of VUF are similar in all three COVID-19-related scenarios. Opposite of analyses of network losses and voltage magnitude, the correlation between VUF and the pandemic is not so noticeable. Values of VUF are

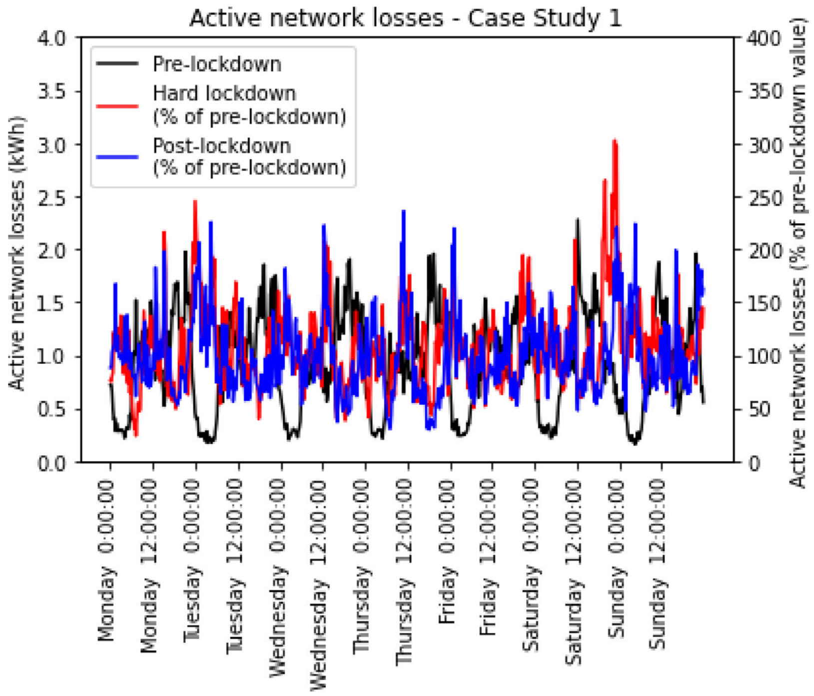

Fig. 2. Active network losses (kWh) - CS1.

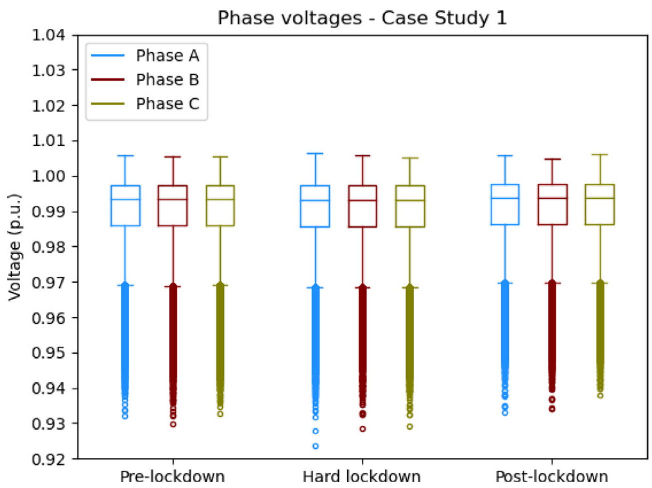

Fig. 3. Phase voltages ($p.u.$) - CS1.

more dependent on the distribution of the demand between the phases, and consequentially, differences between phase voltages. According to the definition of voltage unbalance in [34], the value of VUF should not exceed 0.7% at nodes where end-users are located. As it can be seen inFig.2, the limitation is not violated, no matter the scenario. However, the value of VUF could additionally increase with the uncoordinated integration of single-phase LC units, e.g. PVs.

A tool developed as the pandapower extension is used for unbalanced harmonic analyses [31]. From the network parameters and the harmonic current data used as an input parameter, voltages at non-fundamental frequencies are calculated. The results of the analysis for each observed non-fundamental frequency are shown inFig.5.

As it can be seen inFig.5, the largest harmonic voltage generally occurs in the hard lockdown period. For some frequencies, voltages at some phases are larger during the pre- or post-lockdown period but generally, the magnitude is largest in the hard lockdown period for at least one phase. Harmonic current is one of the parameters used in the calculation of harmonic voltages. Since the higher-order harmonic current is calculated from the current at the fundamental frequency, which increases with the higher electricity consumption, increased values of harmonic voltages in the hard lockdown period are expected. Despite the increased values of harmonic voltages, comparison with the threshold values defined in Section2shows that the values are within allowed boundaries for every non-fundamental frequency.

From calculated harmonic voltages at non-fundamental frequencies and from the value of voltage calculated with unbalanced load flow, it is possible to determine total voltage harmonic distortion (THD_u) for each phase of every node in the network. Values of THD_u in the initial case and its dependence on the COVID-19 pandemic are shown inFig.6.

As it can be seen inFig.6, THD_u values shown in a boxplot are largest during the hard lockdown period. However, some of the outlier values during the post-lockdown values are larger than

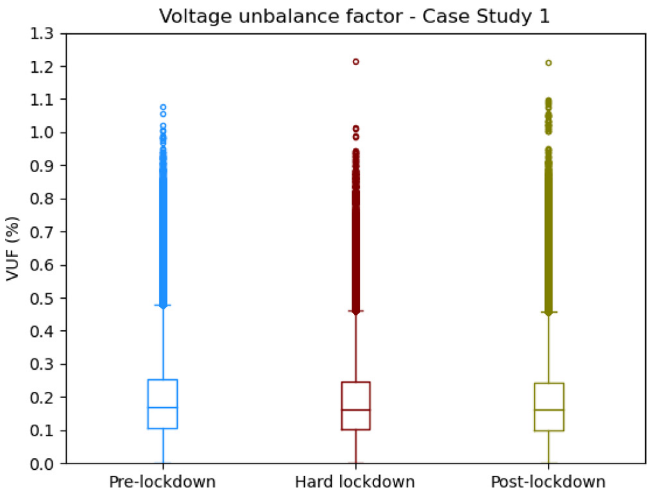

Fig. 4. Voltage unbalance facotr (%) - CS1.

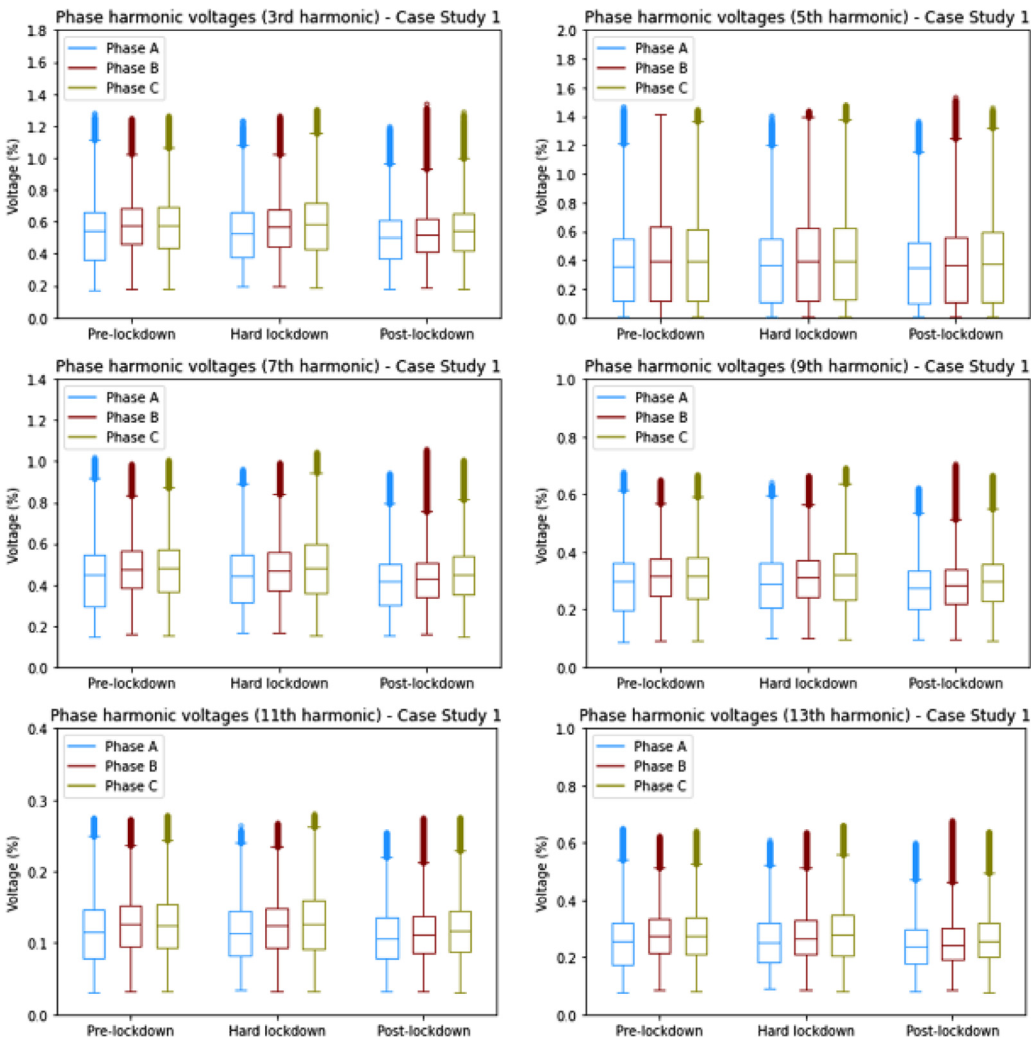

Fig. 5. Phase harmonic voltages (%) - CS1.

those occurring in the hard lockdown period. Those values can be characterized as extreme values and should not be used for general conclusions. Similar to cases of network losses and voltage magnitude, the value of THD_u correlates with electricity demand. Since it is calculated from the values of higher-order harmonic voltages it is also dependent on the values that are the result of the unbalanced harmonic analysis. As mentioned before, values of harmonic voltages are calculated with the defined harmonic current spectrum, and in the case of larger fundamental frequency current, both higher-order harmonics voltages and currents are

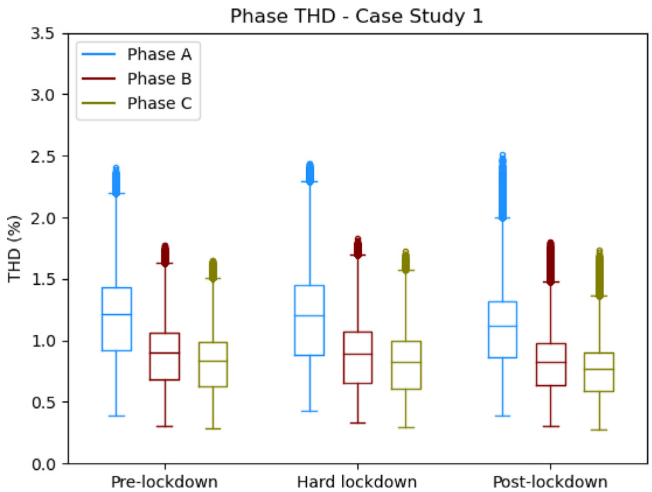

Fig. 6. THD (%) - CS1.

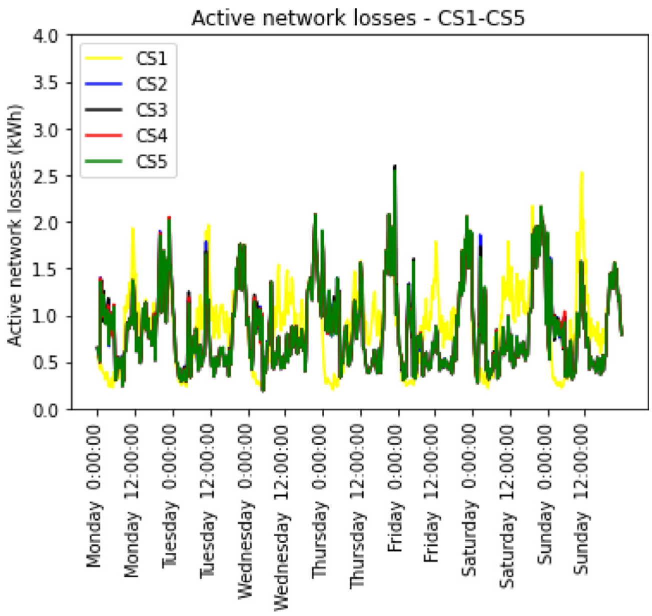

Fig. 7. Active network losses — CS1–CS5.

larger. This consequentially leads to the higher value of THD_u. Even though the hard lockdown period is marked with enlarged values of THD_u, it does not present a significant concern for DSOs due to values far from 8%, which is the defined limitation in LV distribution networks. However, the integration of LC units could cause an additional increase of THD_u and potentially the violation of defined limitations, which will be investigated in further case studies.

4.2. Impact of DERs integration

The integration of DERs is observed through four different case studies (CS2, CS3, CS4, and CS5), defined in Section3. The first case study is used as the benchmark one so that the changes caused by the uncoordinated integration of DERs could be compared to the situation in which there are now LC units in an LV network.

Low-voltage network losses are significantly impacted by the integration of DERs, and the impact can both increase [41] and decrease network losses [42]. Installation of PVs leads to the consumption of locally produced electrical energy and consequentially decreased network losses, while some other technologies, e.g., EVs or heat pumps, lead to increased consumption and increased network losses. As it can be seen inFig.7, active network losses have increased with the integration of DERs. Also, active network losses increase with each case study defined with the increased share of installed LC units. Even though installation of PVs could lead to lower network losses, increased demand caused by heat pumps annuls the effect and causes larger network losses. The trend is especially concerning due to the recent increase in electricity prices, which could lead to additional costs in the planning and operation of active distribution networks. It is important to add that network losses presented inFig.7are calculated as the median value of all scenarios for one time period. Since each scenario defines the share of electricity generating and consuming LC units, an approach in which we present the median value is determined as the best method to cover all differences caused by different scenarios.

As defined in most of the European standards, the limitations must be preserved during 95% of observed time intervals. Therefore the first analysis of the DERs integration is focused on the frequency of violating the limitations defined in [32–34].Fig.8 shows the percentage of nodes in which PQ indicators violate

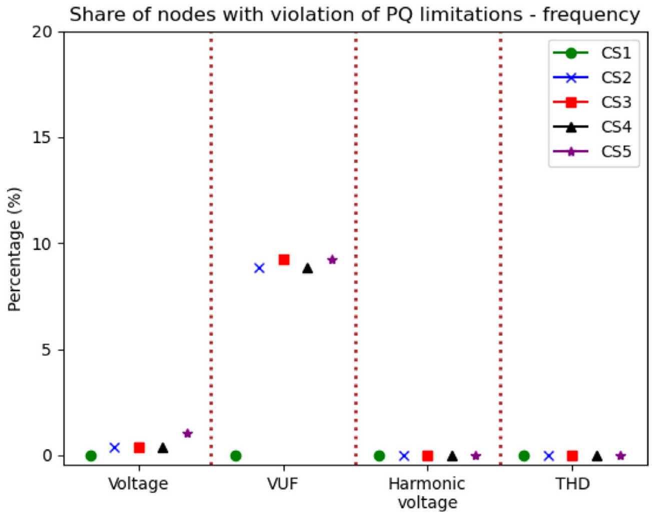

Fig. 8. Share of nodes with violation of PQ limitations — frequency.

the values defined in [32–34] in more than 5% of observed time intervals. Since the simulations were run for different scenarios, only the median value calculated from the values of PQ indicators in all scenarios is presented in Fig. 8 for every analyzed PQ indicator.

In the initial case (CS1), none of the nodes in the defined network have any problem with PQ, i.e., the limitations are not violated in more than 5% of time periods at any of the nodes in an LV network. In CS2, when 20% of end-users have LC units, power quality starts to deteriorate and voltage magnitude limitations are violated in more than 5% of periods at a few nodes, VUF limitations violation happens at almost 10% of nodes. Harmonic analysis shows that the harmonic voltage violations and the violation of THD_u never happen.

When 40% of end-users are equipped with LC units (CS3), the situation is similar to CS2. Violations related to voltage magnitude occur at a few nodes, while those related to VUF occur at more nodes. Since there are a lot of uncertainties in defined scenarios, it is possible that in some scenarios there were more HPs or EVs than PVs, which leads to lower voltage magnitudes in general. Also, the stochastic distribution of LC units among the phases contributes to the increase in unbalance. Same to CS1 and CS2, an increase in LC units' share does not cause problems related to harmonic pollution.

In CS4, problems with voltage magnitude occur at the same share of LV nodes compared to CS 2 and CS3, while the share of nodes facing voltage magnitude violations increases in CS5. Violations of unbalance limitations remain similar in both CS4 and CS5, i.e., VUF violations happen in a fewer nodes, while the share of nodes facing the violations in CS5 is the same as one in CS3. As in all previous cases, there are no violations of harmonic constraints that should consider DSOs.

5. Improvement of PQ indicators

Since both the frequency and value of the violation of PQ limitations present potential challenges for a DSO, there is a need for taking actions and measures that will enable integration of DERs without violation of threshold values for the observed PQ indicators. Otherwise, they could present serious problems, including the increase of technical and economic losses and the deterioration of the equipment's performance. Additional problems are caused by the increased network losses which together with the increased electricity prices present the unexpected costs for a DSO.

To prevent the occurrence of unwanted events in distribution networks following measures are implemented and tested in the defined LV network:

- Increase of lines/cables section (lines/cables replacement) — Method 1
- Three-phase connection of LC units — Method 2
- Phase swapping (balancing) — Method 3
- Volt/Var control — Method 4

The goals, advantages, and disadvantages of each method used for the improvement of PQ and network losses is summarized in Table 2.

Since the implementation of solutions proposed in Method 1 and Method 2 is straightforward, there is no need for their further explanation. Phase swapping (balancing) is made only for single-phase connected PVs and heat pumps and it is explained with Eqs. (4)–(10). Eqs. (4)–(6) define the total power of each phase, while Eqs. (7)–(9) constraint the single-phase connection of LC units. Finally, Eq. (10) presents a function with the goal of minimizing total power differences between the phases. All equations are valid for the nodes affected by the bad power quality, regardless of the observed case study.

$$P_{a,total} = P_{a,demand} - x_{a,pv} \cdot P_{pv} + x_{a,hp} \cdot P_{hp} + x_{a,ev} \cdot P_{ev} \tag{4}$$

$$P_{b,total} = P_{b,demand} - x_{b,pv} \cdot P_{pv} + x_{b,hp} \cdot P_{hp} + x_{b,ev} \cdot P_{b,ev} \tag{5}$$

$$P_{c,total} = P_{c,demand} - x_{c,pv} \cdot P_{pv} + x_{c,hp} \cdot P_{hp} + x_{c,ev} \cdot P_{ev} \tag{6}$$

$$x_{a,pv} + x_{b,pv} + x_{c,pv} = 1 (7)$$

$$x_{a,hp} + x_{b,hp} + x_{c,hp} = 1 (8)$$

$$x_{a,ev} + x_{b,ev} + x_{c,ev} = 1 (9)$$

$$min \quad \{|P_{a,total} - P_{b,total}| + |P_{a,total} - P_{c,total}| + |P_{b,total} - P_{c,total}|\} \tag{10}$$

where $P_{a,total}$, $P_{b,total}$, and $P_{c,total}$ are variables defining the total power of each node, P_{pv} is the parameter defining the PV output power, P_{hp} and P_{ev} are single-phase active powers of heat pumps and electric vehicles. $x_{a,pv}$, $x_{b,pv}$, $x_{c,pv}$, $x_{a,hp}$, $x_{b,hp}$, and $x_{c,hp}$ are binary variables defining that PVs or heat pumps can be connected to the only one phase and ensuring that the optimization algorithm proposes the most adequate phase for the connection

Table 2
Goals, advantages, and disadvantages of the proposed methods.

	Goal	Advantages	Disadvantages
Method 1	Increase of a network' impedance, improvement of the resilience to disturbances	Currents in a network are lower, decrease of network losses, improvement of voltage conditions	An expensive solution, requires a lot of time, especially when replacing underground cables
Method 2	Balancing total load among the phases	More symmetrical distribution of voltages, mitigation of unbalance decreased network losses	Hard to implement, unrealistic to expect to replace all single-phase inverters with three-phase
Method 3	Relocation of power from the most loaded phase	Decreased unbalance, improvement of voltage magnitude and network losses	Installation of phase-switching devices and advanced communication infra-structure
Method 4	Curtailment of active power in order to enable reactive power compensation	Improvement of technical (voltage and current) conditions in a network	Installation of smart inverters and advanced communication infrastructure, possible rebound effect (e.g., charging of EVs)

of each LC unit. It is important to mention that the described approach is valid only for single-phase units while the PVs that are already three-phase connected are not considered since their connection is symmetrical.

Volt/Var control provided by the power electronic devices through which LC units are connected to the network is described with Eqs.(11)–(16). Eqs.(11)–(12)define the apparent power of a LC unit connected to a phase p, while Eqs.(13)–(16)define the values of both active and reactive power in the case of the Volt/Var control. The assumption made in this formulation is that apparent power must remain the same, i.e., power electronic devices cannot be over-dimensioned. To secure that constraint and to ensure providing the Volt/Var control, active power is reduced to 70% of the initial value, before Volt/Var control. The reduced active power is used for the reactive power compensation.

$$S_{p,pv} = P_{p,pv} \tag{11}$$

$$S_{p,hp} = \sqrt{(P_{p,pv})^2 + (Q_{p,pv})^2} \tag{12}$$

$$P_{p,pv,control} = 0.7 \cdot P_{p,pv} \tag{13}$$

$$Q_{p,pv,control} = \sqrt{(S_{p,pv})^2 - (P_{p,pv,control})^2} \tag{14}$$

$$P_{p,hp,control} = 0.7 \cdot P_{p,hp} \tag{15}$$

$$Q_{p,hp,control} = \sqrt{(S_{p,hp})^2 - (P_{p,hp,control})^2} \tag{16}$$

where $S_{p,pv}$ and $P_{p,pv}$ are apparent and active PV power in the initial case, $S_{p,hp}$, $P_{p,hp}$, and $Q_{p,hp}$ are apparent, active, and reactive power of heat pumps in the initial case, while $P_{p,pv,control}$, $Q_{p,pv,control}$, $P_{p,hp,control}$, and $Q_{p,hp,control}$ are active and reactive power of LC units in the case of the Volt/Var control.

Before the implementation of the above-mentioned methods, critical end-users need to be identified. Critical end-users are defined as the ones most affected by the poor PQ, both in terms of frequency and value of the violation of the limitation. Since end-users are not connected to all nodes in an LV network, e.g., to the nodes representing coupling points that connect two line objects, it is not reasonable to observe all nodes as potential locations for the installment of phase switching devices or the replacement of single-phase with three-phase inverters.

A flow chart presenting the steps in the improvement of network losses and power quality is presented inFig.9.

After the end-users nodes are identified, it is necessary to run both unbalanced load flow and harmonic analysis calculations and analyze the results. The analysis of the initial results, without implementing the methods for the PQ improvement is provided in Section4. Since the analysis show that there are nodes affected by poor power quality, the next step is implementation of different measures that should have a positive effect on the PQ indicators, and repeating the process shown inFig.9.

Table3shows the share of nodes with PQ problems related to the frequency of the violation of defined limitations after the implementation of different methods based on the physical devices. Since the results of the initial analysis showed that there were no PQ-related problems during the COVID-19 pandemic, the efficiency of the methods are investigated only for the case studies defined with the different share of installed LC units. Also, solutions defined in Method 2–Method 4 are oriented on the change of LC units' operation and therefore they could not be implemented in the case before the integration of DERs.

Table3shows the results of the PQ improvement in terms of the frequency of violating technical constraints. As it can be seen from the results inTable3, all methods reduced the share of nodes with the frequency of violation of limitations. Method 1, in which cables and lines were replaced with those of the larger segment, has shown to be the worst solution in terms of the PQ improvement. Voltage magnitude violations remain the same in all case studies, and only a small decrease of the share of nodes with the VUF violation occurred in CS3. The absence of harmonic-related problems remained after the increase of cables and lines section. All single-phase inverters at the nodes affected by the PQ problems were replaced by three-phase in Method 2, i.e., all LC units were assumed to be three-phase connected to the network. The results have shown that this method is by far the best in mitigating the PQ problems. All voltage magnitude and VUF violations were successfully solved, with the exception of CS4 where values of VUF are problematic at only one node of CS5 where VUF violated the limitations in more than 5% of time periods at 18.44% of nodes in the LV network. Same as before the replacing of the inverters, there are no problems with the values of harmonic voltages and THD_u. In Method 3, phase swapping devices were assumed to be installed at the nodes that are facing PQ problems. The share of nodes with voltage magnitude violations

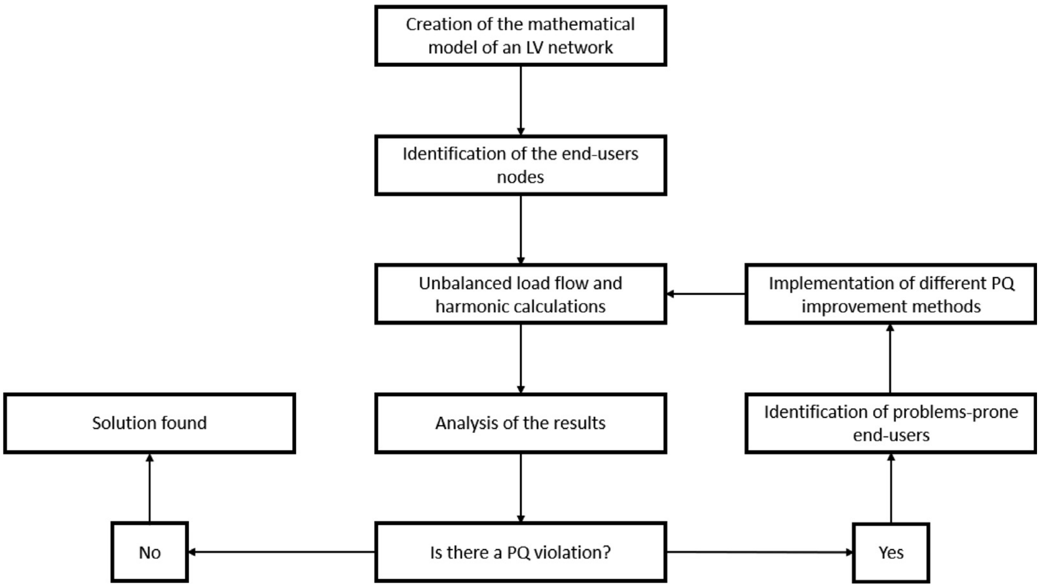

Fig. 9. Improvement of PQ — methodology.

Table 3
Share of nodes with PQ problems — frequency of violation.

		Voltage magnitude	VUF	THD	Harmonic voltage		Voltage magnitude	VUF	THD	Harmonic voltage
CS2	Initial	0.35%	8.87%	0.00%	0.00%	CS3	0.35%	9.22%	0.00%	0.00%
	Method 1	0.00%	12.06%	0.00%	0.00%		0.00%	10.28%	0.00%	0.00%
	Method 2	0.00%	0.00%	0.00%	0.00%		0.00%	0.00%	0.00%	0.00%
	Method 3	0.35%	3.54%	0.00%	0.00%		0.00%	3.55%	0.00%	0.00%
	Method 4	0.00%	14.55%	0.00%	0.00%		0.00%	14.18%	0.00%	0.00%
		Voltage magnitude	VUF	THD	Harmonic voltage		Voltage magnitude	VUF	THD	Harmonic voltage
CS4	Initial	0.35%	8.87%	0.00%	0.00%	CS5	1.06%	9.22%	0.00%	0.00%
	Method 1	0.00%	11.70%	0.00%	0.00%		0.00%	10.99%	0.00%	0.00%
	Method 2	0.00%	0.00%	0.00%	0.00%		0.00%	0.00%	0.00%	0.00%
	Method 3	0.00%	2.84%	0.00%	0.00%		0.00%	3.19%	0.00%	0.00%
	Method 4	0.00%	14.89%	0.00%	0.00%		0.00%	13.48%	0.00%	0.00%

was decreased in all case studies and the violation occurs at only one node in CS4. Even though the phase balancing decreases the share of nodes with voltage unbalance problems, it still remains significant, which could lead to further problems caused by the too high value of voltage unbalance. There are no problems with harmonic pollution. The final implemented method is Method 4 in which power electronic devices of LC units provided Volt/Var control, i.e., they were injecting or consuming reactive power in order to improve voltage conditions in the network. The share of nodes with the problems related to the frequency of violation of voltage magnitude limitations inc CS1 remains the same as in the initial case, while in all other case studies, there are no violations related to the value of voltage magnitude. The share of nodes with the VUF violation problems was decreased and the efficiency of this method is similar to Method 3. Same as for all other methods, there are no problems related to the values of harmonic voltages and THD_u.

The final analysis includes the investigation on the correlation between network losses and the implementation of the methods. Total active network losses calculated as the sum of network losses in all observed time periods are presented inTable4.

The conclusions that can be drawn from the results presented inTable4are similar to ones drawn after the analysis of PQ indicators, i.e., the improvement of PQ consequentially decreases network losses. Even though cable replacement is not the best method in terms of PQ improvement, it is the one that mostly reduces network losses. However, Method 1 presents numerous difficulties, including high financial costs and large construction works. Since the other methods are easier to implement and include installment of the physical devices at the location of an end-user. Three-phase connection of LC units shows to be the best solution in terms of network loss decrease. This suggests a high correlation between voltage unbalance and network losses, since the implementation of Method 2 is mainly oriented toward the mitigation of voltage unbalance. Phase switching also enables a decrease in network losses, while the last method, does not help in the reduction of network losses. All of these results suggest that it is not necessary only to implement a technique but to determine the target phases and devices which are the most suitable for contributing to the decrease of network losses.

To additionally emphasize the importance of this analysis, Tables5and6show financial losses before and after the implementation of every solution. The results correlate with those relevant in the network losses analysis. An important aspect of this analyses is a comparison of financial losses in cases when pandemic and current prices of electricity were used. The electricity prices are day-ahead prices in the Croatian Power Exchange (CROPEX) market. Pandemic prices match with the exact week used for determining the hard lockdown consumption, while the current prices are more relevant nowadays. Since the price of electricity has significantly increased, DSOs need to decrease network losses more than ever. Except Volt/Var control, all other

Table 4
Total active network losses (kWh).

		Active network losses (kWh)				
		Initial	Method 1	Method 2	Method 3	Method 4
CS1	Pre-lockdown	621.698	–	–	–	–
	Hard lockdown	622.390	–	–	–	–
	Post-lockdown	558.430	–	–	–	–
CS2		610.700	450.878	602.368	605.779	731.899
CS3		609.238	450.815	601.963	605.468	731.913
CS4		608.820	450.689	602.016	605.229	731.906
CS5		609.548	450.722	602.431	605.656	731.950

Table 5
Total active network losses costs (€) - pandemic prices.

	Active network losses (kWh)				
	Initial	Method 1	Method 2	Method 3	Method 4
CS1	14494.077	–	–	–	–
CS2	13568.614	9823.064	13335.613	13458.011	16060.788
CS3	13540.908	9848.687	13338.114	13418.012	16063.699
CS4	13533.043	9838.145	13320.368	13390.677	16078.733
CS5	13542.338	9837.714	13314.584	13381.236	16070.834

Table 6
Total active network losses costs (€) - current prices.

	Active network losses (kWh)				
	Initial	Method 1	Method 2	Method 3	Method 4
CS1	194275.879	–	–	–	–
CS2	185483.994	135688.455	183612.141	184662.687	221477.022
CS3	185095.205	135771.134	183631.863	184531.685	221632.140
CS4	184988.255	135793.528	183606.985	184523.848	221649.540
CS5	185167.634	135787.890	183478.899	184680.092	221505.331

solutions tested in this paper show a great potential in economic savings despite the necessity for installing physical devices.

6. Conclusions and future works

The COVID-19 pandemic affected numerous businesses and sectors and also changed people's habits and behavior. The pandemic led to a longer stay at homes for most of the end-users which changed the traditional electricity consumption pattern and created new challenges in the planning and operation of distribution networks.

In this paper, the change of the network losses and values of power quality indicators during different stages of pandemic (pre-lockdown, hard lockdown, and post-lockdown) were analyzed. Due to the increased electricity consumption during the hard lockdown period active network losses increased, values of voltage magnitude decreased, and both higher-order harmonic voltages and THD_u increased. Additionally, the values of VUF also increased. However, voltage unbalance is more dependent on the distribution of consumption among the phases than on the total electricity demand of the end-user.

The other phenomenon analyzed in this paper is the integration of PVs, EVs, and heat pumps. LC units were assumed to be installed at 20%, 40%, 60%, and 80% of LV nodes to which end-users are connected. Their installation is uncoordinated, i.e., the phase of their connection to the network was randomly selected. Since there are lot randomly determined factors, a high number of scenarios determining the phase and the way (single-phase or three-phase) of connection, power of LC units, and different information relevant for the creation of end-users consumption curves. That way the results of the simulation become more relevant in terms of general conclusions since they are not valid for only one specific scenario. The results of the analysis show that even at 20% of LC units in the network power quality starts to deteriorate. The results of analyses show the existence of nodes facing the problems related to the frequency of violation of PQ indicators, which was expected, especially in the case of uncoordinated integration.

To decrease or possibly even completely mitigate the problems caused by the poor power quality four different methods based on the utilization of the physical devices were implemented in the mathematical model. Even though all methods improve active network losses and power quality in the observed LV network, Method 2, in which all LC units are three-phase connected to the network has shown the greatest potential in a decrease of the PQ-related problems, both in terms of the frequency and the value of the violations limitation. Since there were no problems related to harmonic pollution the efficiency of these methods should be tested in the case of larger harmonic distortion.

Most of the conclusions drawn from the results of the simulations were expected and in order to introduce the novelty to the paper, besides using the hard lockdown consumption as a referent one, the correlation between the PQ deterioration and technical and financial losses was investigated. Even though there are other papers showing the dependence of network losses on voltage magnitude and voltage unbalance, to the best of the authors' knowledge, this is the first paper that presents the impact of a comprehensive PQ analysis on the value of active network losses. Additionally, direct financial losses were calculated for the electricity prices during the hard lockdown period and current electricity prices, which are nowadays multiple times higher than they were 2 years ago. These results show the importance of the presented and similar analyses since the integration of LC units is inevitable and DSOs can expect an increase of problems related to increased financial losses and the deterioration of the equipment if they do not react in due time. Therefore, the implementation of the proposed and similar solutions will most likely become a necessity in the planning and operation of DERs-rich distribution networks.

Despite the results that show the potential of the utilization of physical devices, there are still some problems in terms of the implementation of the proposed methods. Not all methods are equally efficient, some methods, e.g., Volt/Var control, do not directly aim at the problematic phase and value and the solution is more generalized, and implementation of three-phase inverters is unrealistic in some scenarios. Due to these and other difficulties, the drawn conclusion should be taken with caution and it is still necessary to run comprehensive simulations that will enable further integration of LC units. Also, the tested network did not face harmonic distortion problems and the efficiency of the tested methods remains unknown. Therefore, future work includes simulations in harmonically polluted LV networks and testing the efficiency of the proposed methods on harmonics improvement. Also, the pandemic did not cause only problems for DSOs but it also created an opportunity for end-users, whose longer stay at home can be used in different flexibility schemes.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Modeling and open source implementation of balanced and unbalanced harmonic analysis in radial distribution networks

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ABSTRACT

With the increasing integration of new technologies, power system operators are facing new operational and planning challenges. Most of these changes are caused by power electronics devices of low carbon (LC) units, resulting in more frequent violations of limits defined in the standards, such as the unwanted occurrence of higher-order harmonics. These aspects indicate that an open source tool, capable of analyzing and estimating future impacts of the above-mentioned phenomena and technologies, would be of great benefit. The paper presents the development of a Phyton-based open source tool as an extension of the existing pandapower library. The upgrade includes the capability of balanced and unbalanced harmonic analysis for LC impact assessment. The technical background and mathematical formulations implemented in the newly developed tool are explained in detail and benchmarked against existing commercial tools showing high accuracy, i.e., the median deviation between the results calculated by the developed and the commercial tool is no larger than 0.21% in the worst-case scenario. In addition to verification, the developed tool is used for the analysis of a real-world network with a high share of LC technologies. The source code of the tool is made available for verification and future updates.

1. Introduction

1.1. Motivation

The installed capacity of the renewable energy sources is continuously growing [1]. Besides the capacity of large power plants connected to the transmission network, the installed capacity of smaller distributed generators (DGs), e.g., PV power plants have increased [2]. The decrease in prices has made the PVs more available to the end-users, leading to a high installed capacity in low-voltage networks, which in some countries can be 70% of total PV capacity [3]. Since the price of other low-carbon (LC) technologies, e.g., battery storage [4], is also decreasing, it is expected that the share of LC technologies will be significantly higher than it is today. Even though some of LC technologies can provide ancillary services and help in the operation of the power system [5], others can lead to voltage [6] and congestion problems [7], increased harmonic distortion [8], voltage unbalance [9], and other unwanted events. Since the share of LC technologies is not expected to fall, it is important to develop adequate tools that can easily assess the impact of LC technologies on power quality (PQ) parameters in a power system. Most of LC units' interfaces to the power system are through power electronic devices and, in addition to a higher share of nonlinear loads, the increased harmonic distortion is becoming an increasing challenge for distribution system operators. Unknown or unallowed values of harmonic distortion can lead to serious problems in the planning and operation of power systems, such as increased thermal losses, tripping of protection, overheating of transformers windings, and decrease in performance.

1.2. Literature review

The assessment of the LC technologies' impact on PQ parameters is a well-known problem and numerous papers have dealt with mitigating one or more problems related to a PQ or other problems in power systems. Research is done using licensed, commercial tools, or open source tools [10–12].

The authorsuthors of paper[13] use NEPLAN for load flow (LF) with load profiles analysis. NEPLAN was used as a tool for assessing the impact of optimal investment decisions from distributed energy resources planning tools on local electricity networks [14]. The same tool was also used for the detection of overvoltages and reverse power flows

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Nomenclature

$\left[\Delta U_{\{\}/abc,h}\right]$ h th order harmonic voltage/phase harmonic voltage drop vector of the power system
$\left[U_{\{\}/abc,h}\right]$ h th order harmonic voltage/phase harmonic voltage vector of the power system
$\left[U_{abc,r/n,h}\right]$ h th order harmonic phase voltage vector of the referent node r/node n in the unbalanced network
$\left[Y_{012/abc,\ k,l}\right]$ sequence/phase admittance matrix of the element between nodes k,l
$\left[Y_{012/abc/\{\}}\right]$ sequence/phase/balanced admittance matrix of the observed network
$\left[Z_{012/abc,r,h}\right]$ sequence/phase impedance matrix of the referent node r for the hth harmonic
$\left[Z_{abc/\{\},\{\}/h}\right]$ phase/balanced impedance matrix of the observed network for the fundamental/hth harmonic
$\delta_{0/1,e}$ angle of the zero/positive sequence impedance of the external grid
$\frac{X_{0,e}}{X_{1,e}}$ external grid's zero sequence to positive sequence reactance
$\frac{X_{0/1,e}}{R_{0/1,e}}$ external grid's zero/positive sequence resistance to reactance ratio
$\varphi_{\{\}/p,n,s,h}$ angle of the harmonic current of the harmonic source s connected three-phase symmetrically/to the phase p to the node n
$\theta_{\{\}/p,n,s,h}$ defined hth order angle of the harmonic current of the harmonic source s connected three-phase symmetrically/to the phase p to the node n
c voltage factor
$I_{\{\}/p,n,s,h}$ h th order harmonic current of the harmonic source s connected three-phase symmetrically/to the phase p to the node n
$i_{\{\}/p,n,s,h}$ defined hth order harmonic current of the harmonic source s connected three-phase symmetrically/to the phase p to the node n expressed as the percentage of the fundamental harmonic
$I_{\{\}/p,r,h}$ h th order harmonic current of the referent node r connected three-phase symmetrically/to the phase p
$R_{0/1\ k,l}$ zero/positive sequence resistance of the element between nodes k,l
$R_{0/1,e}$ zero/positive sequence resistance of the external grid
S_B base apparent power
$S_{\{\}/p,n}$ power of the load/generator connected to the node n/phase p of the node n
S''_{SC} three-phase short circuit power
$THD_{i,p,n}$ total current harmonic distortion of the phase p of the node n
$THD_{u,p,n}$ total voltage harmonic distortion of the phase p of the node n
U_n nominal voltage
$U_{0/1/2,n}$ zero/positive/negative sequence voltage of the node n
$U_{\{\}/p,n,1}$ voltage of the phase p of the node n
$U_{r/n,h}$ h th order harmonic voltage of the referent node r/node n in the balanced network
$X_{0/1\ k,l}$ zero/positive sequence reactance of the element between nodes k,l
$X_{0/1,e,h}$ zero/positive sequence reactance of the external grid for the hth harmonic
$X_{L/C,h}$ inductive/capacitive reactance for the hth harmonic
$Y_{0/1/2\ k,l}$ zero/positive/negative sequence admittance of the element between nodes k,l
$Z_{0/1,e,h}$ zero/positive sequence impedance of the external grid for the hth harmonic
$Z_{0/1/2\ k,l}$ zero/positive sequence impedance of the element between nodes k,l
$Z_{0/1/2,e,h,p.u.}$ zero/positive/negative sequence impedance of the external grid for the hth harmonic
$|Z_{0/1,e}|$ magnitude of the zero/positive sequence impedance of the external grid
$|I_{\{\}/p,n,s,h}|$ magnitude of the harmonic current of the harmonic source s connected three-phase symmetrically/to the phase p to the node n

caused by the PV [15].

The optimal penetration level of PV systems in the distribution network considering both power loss reduction and protection miscoordination cost to maximize the profit of the Distribution System Operator is determined using ETAP [16]. The paper [17] presents the effect of an EV parking lot equipped with a roof-mounted PV type solar power plant on the distribution network along with the simulations in the ETAP environment considering physical location limitations. ETAP is used for the LF analysis and the short circuit calculation as a preprocess to the proposal of the combined fuse and numerical relays inter-linked with digital logic-based adaptive overcurrent protection scheme [18].

DigSILENT PowerFactory is used for the voltage stability analysis of the simplified distribution feeder in time domain simulations [19]. In [20], a reactive power-voltage-based framework to evaluate the voltage instability sensitivities of power system buses with the increase in renewable energy penetration has been developed using DigSILENT PowerFactory for performing the simulations of the test grid. Effects of increasing solar connections which are realistic in near future have been analyzed by modeling the detailed network in DigSILENT PowerFactory simulation platform [21].

The above-mentioned and other commercial power system analysis tools are often used because of their reliability, different analyses possibilities, intuitiveness, and other numerous advantages. However, they are often expensive, and since they are licensed, it is not always easy to automatize the processes or to connect them with other tools. Therefore the number of power system analyses made by using open source tools is growing.

Thurner et al. [22] describe pandapower, an open source Python tool, used for automation of static and quasi-static analysis and optimization of both balanced and unbalanced systems. The implementation of IEC 60909 short circuit calculation in pandapower was presented another paper that describes the mathematical formulation behind the tool's development [23]. The same tool was used for the reconfiguration of a distribution network, where pandapower elements and functions were used in finding an optimal topology based on a reinforcement learning approach [24].

Zimmerman et al. [25] present MATPOWER, an open source Matlab-based power system analysis tool, similar to pandapower, which can be used for different network analyses. Balanced LF functionality of MATPOWER is used for solving the problem of unit commitment and economic dispatch in microgrids [26]. The combination of speed of MATPOWER and the search capabilities of a meta-heuristic optimization algorithm was used to find the optimal location of an electric vehicle charging station in a local microgrid [27].

OpenDSS, an open source tool specialized in unbalanced power systems, can be used for power flow and harmonic LF analyses, whose results are the input for optimal energy scheduling and a power quality improvement of a microgrid [28]. OpenDSS is also usedto investigate the synergy between uncontrolled charging of plug-in EVs and the energy generation from wind-based DGs [29]. The authors in paper [30] use OpenDSS software for power flow analysis and the evaluation of voltage unbalance, steady-state voltage, and transformer load for the assessment of the potential benefits the connection of PVs can bring to a commercial building with EV charging stations.

Most open source tools are validated against commercial ones and show differences no larger than 0.08% [31,32]. Therefore, they are often used in simulations of power systems. Since they are free and do not require expensive licenses, they can be used in automatized processes, can easily be connected with external databases, and combined with other tools. Most importantly, the open source approach allows easier further upgrade and development. However, open source tools often do not have the same analytical capability compared to commercial tools, the methodology is often not documented, their use often requires programming capabilities, whereas commercial tools have graphical user interfaces.

1.3. Contributions

Even though the mathematical formulation of both balanced and unbalanced harmonic analysis is a well-known problem, defined and described in detail in numerous papers [33–36], such papers only present mathematical models, and often lack verification and application of the presented model. Additionally, this paper presents a summarized and detailed mathematical formulation for harmonic analyses in both balanced and unbalanced radial distribution networks. The mathematical model can be used in further implementations of harmonic assessment but also as a basis for the upgrade of the developed tool. Since most of the tools lack the information about the implementation of the mathematical model used in different analyses, this paper enables a better understanding of the idea behind the implementation. The detailed mathematical model also enables easier defining of needed input data when using the tool in different harmonic analyses. Despite the existence of papers that present the results of harmonic calculations and analyses based on open source tools [28,37,38], none of them give a detailed mathematical model of harmonic analysis, and they are often not verified against other software, which can make the correctness of results questionable. In addition, even though they are free to use, their formulation is not publicly available and they cannot be further upgraded. To overcome all the above-mentioned issues, a harmonic analysis tool developed as an extension of the pandapower Python-based open source tool is presented in this paper. A detailed mathematical background, used as a basis for the development is presented in detail. Also, the developed tool is validated on both balanced and unbalanced radial distribution networks against NEPLANand DigSILENT PowerFactory commercial tools. To additionally emphasize the benefits and possibilities of the developed tool, a real-world LV network with a high share of EVs is analyzed with harmonic time series simulations, using the developed tool. The developed tool is also publicly available and can be accessed at any time [39], which makes any possible further upgrades easier to implement.

The rest of the paper is organized as follows: Section 2 briefly introduces the detailed mathematical background and the methodology with explained equations used for the calculation of harmonics-related values. Section 3 presents the verification of the developed tool on several test networks. To additionally show the potential and the importance of the developed tool, a real-world network with different scenarios defining the share of PVs and EV charging stations is analyzed in a case study defined in Section 4. Finally, Section 5 highlights the conclusions and plans for future upgrades of the developed tool.

2. Mathematical background and modeling

2.1. Impedance matrix

To calculate THD_u, higher-order harmonic voltages of the referent node and all other nodes must be calculated. The first step of the development of the open source tool is the calculation of the impedance matrix since harmonic voltages are calculated using the impedance matrix for each frequency and harmonic currents at each node. The same step is needed for LF calculations both in balanced and unbalanced power systems. In the case of unbalanced networks, the creation of an impedance matrix is possible by using sequence components or by using a three-phase approach. Since a lot of the LV network data, acquired from the DSO, is given with sequence values, authors in paper [40] define sequence matrix for both power systems with grounded and without grounded neutral voltage. The sequence matrix can be used in further calculations or it can be transformed into the phase impedance matrix, depending on the needs or representation preferences.

The parameters of the lines in the distribution systems are defined with the resistance and the reactance of the positive and zero systems. The resistance and the reactance of the positive and the negative system are the same for passive power system elements, such as lines and transformers. The impedance of the positive and zero system of the element (e.g., transformer or line) that connects nodes k and l is calculated using (1) and (2).

$$Z_{1\ k,l} = R_{1\ k,l} + jX_{1\ k,l}\ [\Omega] \tag{1}$$

$$Z_{0\ k,l} = R_{0\ k,l} + jX_{0\ k,l}\ [\Omega] \tag{2}$$

$$[Y_{012\ k,l}] = \begin{bmatrix} Y_{0\ k,l} & 0 & 0 \\ 0 & Y_{1\ k,l} & 0 \\ 0 & 0 & Y_{2\ k,l} \end{bmatrix} \tag{3}$$

$$[Y_{abc\ k,l}] = [A]^{-1}[Y_{012\ k,l}][A] \tag{4}$$

$$[A] = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \quad \text{where } a = 1\angle 120^{\circ} \tag{5}$$

The newly developed tool relies on already developed pandapower functions such as that of creating sequence admittance matrices Y_0, Y_1, and Y_2 in per-unit values. Created matrices are valid for the whole observed network and admittance between every two elements of the network can be extracted. The first row and column of each matrix are removed since they present the admittance between referent and other nodes.

Matrix $Y_{012\ k,l}$ is created for each element of matrices Y_0, Y_1, and Y_2 as shown in (3). Using (4) and (5), the sequence admittance matrix is transformed to the phase admittance matrix $Y_{abc\ k,l}$.

From each created $Y_{abc\ k,l}$ matrix the Y_{abc} matrix of the entire network is created (6). The dimension of the matrix is $3\cdot(n-1)\times 3\cdot(n-1)$ since the rows and columns related to the referent node are removed.

$$[Y_{abc}] = \begin{bmatrix} Y_{aa\ 1,1} & Y_{ab\ 1,1} & Y_{ac\ 1,1} & \cdots & Y_{aa\ 1,n} & Y_{ab\ 1,n} & Y_{ac\ 1,n} \\ Y_{ba\ 1,1} & Y_{bb\ 1,1} & Y_{bc\ 1,1} & \cdots & Y_{ba\ 1,n} & Y_{bb\ 1,n} & Y_{bc\ 1,n} \\ Y_{ca\ 1,1} & Y_{cb\ 1,1} & Y_{cc\ 1,1} & \cdots & Y_{ca\ 1,n} & Y_{cb\ 1,n} & Y_{cc\ 1,n} \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ Y_{aa\ n,1} & Y_{ab\ n,1} & Y_{ac\ n,1} & \cdots & Y_{aa\ n,n} & Y_{ab\ n,n} & Y_{ac\ n,n} \\ Y_{ba\ n,1} & Y_{bb\ n,1} & Y_{bc\ n,1} & \cdots & Y_{ba\ n,n} & Y_{bb\ n,n} & Y_{bc\ n,n} \\ Y_{ca\ n,1} & Y_{cb\ n,1} & Y_{cc\ n,1} & \cdots & Y_{ca\ n,n} & Y_{cb\ n,n} & Y_{cc\ n,n} \end{bmatrix} \tag{6}$$

After the phase admittance matrix is created, the phase impedance matrix Z_{abc} is calculated as the inverse of the admittance matrix (7).

$$[Z_{abc}] = [Y_{abc}]^{-1} \tag{7}$$

When a balanced, symmetrical network is observed, there is no need to calculate a three-phase or sequence component matrix. The impedance matrix is calculated using only the positive system values of the lines (1). By using pandapower functionalities, it is possible to get the admittance matrix in per unit values (8). Since the model of the harmonic calculation presented in this paper uses the impedance matrix, the Y matrix (8) needs to be inverted (9).

$$[Y]=\begin{bmatrix} Y_{1,1} & \dots & Y_{1,n} \\ \vdots & \ddots & \vdots \\ Y_{n,1} & \dots & Y_{n,n} \end{bmatrix} \tag{8}$$

$$[Z]=[Y]^{-1} \tag{9}$$

2.2. Voltage and current harmonic distortion

The impedance matrices calculation defined in 2.1 are valid for a base frequency of 50 Hz. To calculate higher-order harmonics, the impedance matrix must be determined for each frequency at which the harmonic distortion is calculated. It is assumed that the resistance of the elements does not change with the frequency, since in distribution networks, especially in LV networks, the dependence on the frequency is not as expressed as in the transmission networks. In most of the European standards which define limitations for distribution networks, higher-order harmonics are defined for a maximum of 2 kHz. For frequencies so high, neglecting a frequency-resistance dependence will not significantly affect the accuracy of the model. The inductive reactance changes with the frequency, according to (10) and (11). In case when the reactive capacitance is known, it changes according to (12) and (13). Mentioned equations are valid for modeling each element defined with the resistance and the reactance.

$$X_{L,h}=2\cdot\pi\cdot 50\,\mathrm{Hz}\cdot h\cdot L \tag{10}$$

$$X_{L,h}=h\cdot X_{L,1} \tag{11}$$

$$X_{C,h}=\frac{1}{2\cdot\pi\cdot 50\,\mathrm{Hz}\cdot h\cdot C} \tag{12}$$

$$X_{C,h}=\frac{X_{C,1}}{h} \tag{13}$$

According to Ćuk et al. [41] transformers can be represented with an equivalent series RL model for lower frequencies, i.e., the reactance of a transformer can be calculated using (10) and (11). Similar to lines, the frequency dependency of the transformer's resistance can be neglected. Both for lines and transformers, the frequency dependency of the resistance can be considered by accurate [42] or simple, approximate models [43]. Initially, different models were implemented in the tool, and simulations were made using those models. However, the results have shown the detailed model does not significantly improve the accuracy of the developed tool. Hence, it is omitted in the final version of the algorithm.

Eqs. (10) –(13) are used for the positive, the negative, and the zero system sequence, with values valid for each of the sequence systems. Since the assumption in this paper is that the resistance does not change with the frequency, from the resistance at the fundamental frequency (50 Hz) and the admittance at each non-fundamental frequency, a three-phase impedance matrix is calculated for every observed higher-order harmonic, according to the Eqs. (1)–(7). In the case of a balanced network, the logic of calculating an impedance matrix remains the same for every higher-order harmonic, and a matrix is determined by using Eqs. (1), (8) and (9).

After the impedance matrix is calculated, the nodal current of each node n (for the balanced systems analyses) or the current of each phase p of the node n (for unbalanced systems analyses) needs to be calculated. The node current is calculated from the apparent power of the load/generator $S_{n,s}$ connected to the node and the node voltage U_n (14), which is the result of the LF calculation. When the network is unbalanced, the harmonic current of each phase p of the observed node n is calculated from the apparent power of the load/generator $S_{n,p,s}$ connected to the phase p of the node n and the node phase voltage $U_{n,p}$ (15), which is the result of the unbalanced LF calculation. Every load/generator is a harmonic source, injecting the harmonic current into the network. If a generator or a load in the analysis does not inject the harmonic current it can be defined with the current of zero amperes for each higher-order harmonic. The power and the voltage are per-unit values. Therefore, the calculated current is also a per-unit value. Using per-unit values in the mathematical formulation is of great benefit, due to the possibility of determining harmonic problems in networks with multiple voltage levels. It is particularly important due to the penetration of RES in distribution networks and bi-directional power flows, as otherwise, the system operators would not be able to analyze multiple voltage levels.

$$I_{n,s,1}=\frac{S_n^*}{\sqrt{3}\cdot U_{n,1}} \tag{14}$$

$$I_{p,n,s,1}=\frac{S_{p,n}^*}{U_{p,n,1}} \tag{15}$$

Since both the power and the voltage are complex numbers, the harmonic current of the node is also defined as a complex number and it can be presented in the polar form. Most devices that cause harmonic distortion are considered as harmonic sources and are defined with the harmonic spectra consisting of magnitude and phase angle. Also, the values of voltages in LF calculations are described with magnitude and phase angles. Therefore, it is common to use the polar form instead of the Cartesian form. Eq. (16) presents the polar form of the hth order harmonic current of the node n, and the harmonic source s in case of a balanced network, i.e., $|I_{n,s,h}|$ is the higher-order harmonic current magnitude and $\angle\varphi_{n,s,h}$ is the phase angle of the same current. When a network is unbalanced, the hth harmonic order current of the node n is calculated for each phase p and each harmonic source s (17).

$$I_{n,s,h}=|I_{n,s,h}|\angle\varphi_{n,s,h} \tag{16}$$

$$I_{p,n,s,h}=|I_{p,n,s,h}|\angle\varphi_{p,n,s,h} \tag{17}$$

Both nodal and phase current are obtained from the base frequency current calculation, the percentage, and the phase angle of the higher-order frequencies. The percentage of the higher-order frequency is defined as the share of the hth order harmonic current in the fundamental harmonic. Both the percentage and the phase angle are defined as input parameters of the harmonic calculation, and they need to be defined for every element that injects harmonic current into a network. When a network is balanced, the harmonic analysis can be done by taking into consideration only the positive sequence system or by considering positive, negative, and zero sequence systems.

When only positive sequence is considered, the nodal current of the hth order harmonic and the harmonic source s is calculated according to (18)–(20). When calculating higher-order harmonics, only the magnitude of the fundamental harmonic current is considered, since in most cases the current of fundamental harmonic is defined with the percentage value of 100% that represents the magnitude and without the angle.

$$I_{n,s,h}=|I_{n,s,1}|\cdot i_{n,s,h}\angle\left(h\cdot\theta_{n,s,h}+240^\circ\right) \tag{18}$$

$$|I_{n,s,h}|=|I_{n,s,1}|\cdot i_{n,s,h} \tag{19}$$

$$\angle\varphi_{n,s,h}=h\cdot\theta_{n,s,h}+240^\circ \tag{20}$$

The detailed methodology and the logic behind the implementation of Eqs. (16)–(20) are presented in Xu [33], Modeling [34]. These equations are basic equations needed for the harmonic analysis model described in this paper. Moreover, as defined in Xu [33], this model is the most common one used in commercial power system harmonic analysis programs and is therefore used in the development of the open source harmonic analysis program.

When the system is balanced, and all three sequence systems are observed, the current is calculated depending on the harmonic order. Under the balanced situation, the positive sequence components can be used to represent the balanced harmonic component with order $h = 3 \cdot m + 1$, the negative sequence component can be used when the harmonic order is $h = 3 \cdot m + 2$, and the zero sequence can be used when the harmonic order is $h = 3 \cdot m$, as defined in Zheng et al. [44], Manjure and Makram [45]. In the case when all sequence systems are observed magnitudes of harmonic currents are calculated the same as in the case when only the positive sequence system is considered (19), and angles of the harmonic currents are calculated using equations defined in (21).

$$\angle \varphi_{n,s,h} = \begin{cases} h \cdot \theta_{n,s,h} & , h = 3 \cdot m \\ h \cdot \theta_{n,s,h} + 240^{\circ} & , h = 3 \cdot m + 1 \\ h \cdot \theta_{n,s,h} + 120^{\circ} & , h = 3 \cdot m + 2 \end{cases} \tag{21}$$

When the three-phase unbalanced radial distribution network is observed, the calculation of the harmonic angles needs to be modified since all sequence systems have an impact in determining the angles of the harmonic currents. Angle φ of each phase p of node n and the harmonic source s for the hth order harmonic is calculated with Eqs. (22)–(24). The calculation of phase angles in harmonic analysis of unbalanced radial distribution networks is just an extension of the equations valid for balanced distribution networks defined in Zheng et al. [44], Manjure and Makram [45].

$$\varphi_{a,n,s,h} = \angle \left(h \cdot \theta_{a,n,s,h} \right) \forall h \tag{22}$$

$$\varphi_{b,n,s,h} = \begin{cases} h \cdot \theta_{b,n,s,h} & , h = 3 \cdot m \\ h \cdot \theta_{b,n,s,h} + 240^{\circ} & , h = 3 \cdot m + 1 \\ h \cdot \theta_{b,n,s,h} + 120^{\circ} & , h = 3 \cdot m + 2 \end{cases} \tag{23}$$

$$\varphi_{c,n,s,h} = \begin{cases} h \cdot \theta_{c,n,s,h} & , h = 3 \cdot m \\ h \cdot \theta_{c,n,s,h} + 120^{\circ} & , h = 3 \cdot m + 1 \\ h \cdot \theta_{c,n,s,h} + 240^{\circ} & , h = 3 \cdot m + 2 \end{cases} \tag{24}$$

In case when there are S different harmonic sources connected to the same node n, the resulting hth order nodal harmonic current is calculated as the sum of harmonic currents injected by every harmonic source s, as shown in Eqs. (25) and (26).

$$I_{n,h} = \sum_{s=1}^{S} I_{n,s,h} \tag{25}$$

$$I_{p,n,h} = \sum_{s=1}^{S} I_{p,n,s,h} \tag{26}$$

Since the impedance matrix and harmonic current injections are determined both for balanced and unbalanced power systems, the system harmonic voltage drop is calculated by direct solution of the linear Eqs. (27) and (28), both for balanced and unbalanced networks [46].

$$[\Delta U_h] = [Z_h] \cdot [I_h] \tag{27}$$

$$[\Delta U_{abc\ h}] = [Z_{abc\ h}] \cdot [I_{abc\ h}] \tag{28}$$

When a balanced network is observed, and the impact of the zero and the negative sequence system cannot be neglected, the direct solution of the linear Eq. (27) needs to be modified. Since the positive sequence and the negative sequence impedance are set to be equal, in the case of the harmonic order $h = 3 \cdot m + 1$ or $h = 3 \cdot m + 2$, the impedance matrix created using only the positive sequence values can be used in voltage drop calculations for those harmonics. However, when the harmonic order is $h = 3 \cdot m$, $[Z_h]$ used in (28) must be created with only zero sequence values, same as in (8) and (9). Even when the harmonic order is $h = 3 \cdot m$, the mathematical model for the calculation of harmonic voltage drop remains the same. The only difference is that the elements in the impedance matrix are defined with zero sequence values.

In order to calculate the higher-order harmonic voltage of each node, it is necessary to calculate the voltage of the referent node for each of the higher-order harmonics. Similar to calculating the voltage drop, the impedance and the current of the referent node must be determined to calculate the voltage. The positive sequence impedance of the external grid in per-unit values is defined with Eqs. (29)–(34). Voltage factor c is used as a parameter in calculating the impedance of an external grid. It is used in short-circuit calculations in order to scale the equivalent voltage source. Since the impedance of an external grid is calculated from the three-phase short-circuit power, it is used in the calculations. Depending on the case, the value of the factor can vary between 0.95 and 1.1. In the examples presented in this paper, the used value is equal to 1, but it can be changed when using the tool, according to the user's preferences.

$$|Z_{1,e}| = c \cdot \frac{U_n^2}{S_{SC}''} \tag{29}$$

$$\delta_1 = \arctan \frac{X_{1,e}}{R_{1,e}} \tag{30}$$

$$R_{1,e} = |Z_{1,e}| \cdot \cos\delta_1 \tag{31}$$

$$X_{1,e} = |Z_{1,e}| \cdot \sin\delta_1 \cdot h \tag{32}$$

$$Z_{1,e,h} = R_{1,e} + j \cdot X_{1,e,h} \tag{33}$$

$$Z_{1,e,h,\ p.u.} = Z_{1,e,h} \cdot \frac{S_B}{U_n^2} \tag{34}$$

In cases of harmonic analyses, the impedance of zero sequence needs to be determined for the referent node voltage calculation. The zero sequence impedance is calculated according to the Eqs. (35)–(40).

$$|Z_{0,e}| = |Z_{1,e}| \cdot \frac{X_{0,e}}{X_{1,e}} \tag{35}$$

$$\delta_0 = \arctan \frac{X_{0,e}}{R_{0,e}} \tag{36}$$

$$R_{0,e} = |Z_{0,e}| \cdot \cos\delta_1 \tag{37}$$

$$X_{0,e} = |Z_{0,e}| \cdot \sin\delta_1 \cdot h \tag{38}$$

$$Z_{0,e,h} = R_{0,e} + j \cdot X_{0,e,h} \tag{39}$$

$$Z_{0,e,h,\ p.u.} = Z_{0,e,h} \cdot \frac{S_B}{U_n^2} \tag{40}$$

The calculation of an external grid's impedance and other parameters important for harmonic analysis is defined with Eqs. (29)–(40). These equations are used in different power system analyses, e.g., short-circuit calculations, and a similar form of the described mathematical model is used in commercial tools such as NEPLAN or Power Factory.

When a distribution network is balanced, and all three sequence systems are considered, then the harmonic impedance of the referent node is equal to the harmonic impedance of the external grid positive sequence impedance (34) when $h = 3 \cdot m + 1$ or $h = 3 \cdot m + 2$, and is equal to the harmonic impedance of the external grid's zero sequence impedance (40) when $h = 3 \cdot m$. When the zero and the negative systems are neglected, no matter the harmonic order, the harmonic impedance of the referent node is equal to the harmonic impedance of the external grid's positive sequence impedance (34).

For an unbalanced network, once the positive and the zero sequence impedance are calculated, the nodal sequence impedance matrix is created (41), with the assumption that the positive and negative sequence impedance are the same. Since the voltage drop is calculated for each phase and not for sequence systems, the sequence impedance matrix is transformed to the phase impedance matrix for each harmonic order h using (42).

$$[Z_{012,r,h}] = \begin{bmatrix} Z_{0,e,h,\ p.u.} & 0 & 0 \\ 0 & Z_{1,e,h,\ p.u.} & 0 \\ 0 & 0 & Z_{2,e,h,\ p.u.} \end{bmatrix} \tag{41}$$

$$[Z_{abc,r,h}] = [A]^{-1}[Z_{012,r,h}][A] \tag{42}$$

The harmonic current of the referent node is equal to the total current injected into the network, for each harmonic order h. The total injected current is calculated as the sum of currents that flow through elements that connect referent and other nodes of an observed network. When the network is balanced, the nodal harmonic current is calculated using (43), and when the network is unbalanced the nodal harmonic current is calculated with (44).

$$I_{r,h} = \sum_{r:r\to n} I_{r,n,h} \tag{43}$$

$$I_{p,r,h} = \sum_{p,r:r\to n} I_{p,r,n,h} \tag{44}$$

Even though calculating the harmonic current of the referent node can be simplified using (45) and (46) in cases when only a positive sequence system is observed, when there are no transformers in a network or their vector group is e.g., Yy0. However, this simplification fails when a vector group of a transformer blocks zero sequence current, e.g., a vector group is Dyn. Therefore it can be used in a limited number of analyses, and it is not used in the implementation of the described mathematical model. The calculation of harmonic current is necessary for each element so that the current of the referent node can be determined.

$$I_{r,h} = \sum_{n=1}^{N} I_{n,h} \tag{45}$$

$$I_{p,r,h} = \sum_{n=1}^{N} I_{p,n,h} \tag{46}$$

When the harmonic impedance and the nodal current of the referent node are calculated, the referent node harmonic voltage for every harmonic order h is calculated with (47) for balanced power systems and (48) for unbalanced power systems.

$$U_{r,h} = Z_{r,h} \cdot I_{r,h} \tag{47}$$

$$[U_{abc,r,h}] = [Z_{abc,r,h}] \cdot [I_{r,p,h}] \tag{48}$$

After the voltage of the referent node and voltage drops for every other node are calculated, the nodal voltage for every harmonic order is created using (49) and (50).

$$U_{n,h} = U_{r,h} - \Delta U_{n,h} \tag{49}$$

$$[U_{abc,n,h}] = [U_{abc,r,h}] - [\Delta U_{abc,n,h}] \tag{50}$$

From nodal harmonic voltages, the system harmonic nodal voltage vector is created for balanced (51) and unbalanced power systems (52) and (53).

$$[U_h] = \begin{bmatrix} U_{1,h} \\ \vdots \\ U_{n,h} \end{bmatrix} \tag{51}$$

$$[U_{abc,h}] = \begin{bmatrix} [U_{abc,1,h}] \\ \vdots \\ [U_{abc,n,h}] \end{bmatrix} \tag{52}$$

$$[U_{abc,n,h}] = \begin{bmatrix} U_{a,n,h} \\ U_{b,n,h} \\ U_{c,n,h} \end{bmatrix} \tag{53}$$

It is important to mention that the calculation of harmonic voltage drop described by the above equations is not the only possible approach in harmonic analyses. Similar to power flow calculations, there are other methods, e.g., backward-forward-based methods, that can be used in the harmonic pollution assessment. The implementation of such methods is planned for the future upgrades of the tool presented in this paper.

When the values of the harmonic voltages are determined, it is possible to determine $THD_{n,u}$ for every node of the observed network (54), defined in the standards [47], 48]. This approach can be extended to the calculation of THD_u of each phase in unbalanced distribution networks.

$$THD_{u,n} = \sqrt{\sum_{h=2}^{H} \left(\frac{U_{n,h}}{U_1}\right)^2} \tag{54}$$

The majority of the description of the mathematical model is related to the calculation of node harmonic voltages. However, harmonic currents can potentially cause problems in distribution networks. Therefore, some of the European standards [47,48] also focus on current total harmonic distortion (THD_i). Calculation of harmonic current at each node is already described with Eqs. (16)–(26). From the calculated node currents, it is possible to calculate $THD_{i,n}$ for each node of a network (55). Similar to the voltage-related calculation of THD, after a small modification, Eq. (55) can be used in analyses of unbalanced distribution networks.

$$THD_{i,n} = \sqrt{\sum_{h=2}^{H} \left(\frac{I_{n,h}}{I_1}\right)^2} \tag{55}$$

3. Verification and test cases

As an update to pandapower, the developed harmonic analysis tool is verified against commercial tools NEPLAN and DigSILENT Power Factory. To compare the results, four test cases were created. To verify all three developed versions of the tool, a case of the balanced harmonic analysis considering only positive sequence (Type I), considering all sequence systems (Type II), and the unbalanced harmonic analysis (Type III) are developed. The balanced harmonic analysis functionality is defined differently in Power Factory compared to NEPLAN and the tool presented in this paper. It is not possible to observe all three sequence systems under the balanced condition, and therefore the developed tool could be verified against Power Factory only for Type I analysis.

The verification of the tool is made by determining the deviation between the results calculated by the tool presented in this paper and commercial tools NEPLAN and Power Factory. The deviation is defined as an absolute value of the difference of the results calculated by both tools. The deviations between the results of each phase, each node, and each harmonic order are compared, but only the maximum, minimum, and median deviations are presented in this paper. Generally, the deviation is calculated as an absolute value between the results obtained by the developed and a commercial tool,r according to equation (56):

$$\Delta_{tools} = \left| v_{n,p,h\ referent} - v_{n,p,h\ pandapower} \right| \tag{56}$$

where Δ_{tools} is the deviation between two tools, $v_{n,p,h\ referent}$ is the referent value determined with NEPLAN or Power Factory, and $v_{n,p,h\ pandapower}$ is the value calculated with the tool developed as the pandapower extension and presented in this paper.

The maximum deviation is calculated as the maximum value between all calculated deviations, both for THD values and harmonic voltages. Similarly, the minimum deviation is taken as the lowest difference between values calculated by the tools. The third observed deviation is calculated as the median value of all determined deviations.

To validate the developed tool, four different test cases were created. Each of the test cases represents a radial balanced or unbalanced distribution network.

3.1. Test Case I

A simple three-bus MV network was created where the external grid is connected to the first node of the network, and the loads are three-phase connected to the two remaining nodes. The topology of the network is presented in Fig. 1. Both loads are defined as the harmonic source, i.e., they are injecting harmonic current in the network.

Table 1 shows the deviation between THD_u, U_h THD_i, and I_h calculated with the developed tool and commercial tools.

The results of the verification show no deviation larger than 0.01% when two tools are compared. The harmonic voltages are the same for every node and frequency, only when calculating THD a small difference occurs in some nodes. In the case of currents, both higher order harmonic currents and THD are the same for every node. Despite the small and insignificant deviation, the tested network is simple and before using the developed tool for analyses of larger, more complex networks it should be further validated.

3.2. Test Case II

A synthetic network defined by Kerber [49] is used for the verification of the developed tool. The topology of the network is presented in Fig. 2. The network consists of the external grid connected to the 10 kV node, transformer, 17 0.4 kV node, and lines that connect nodes. The loads are connected to eight nodes, and each load is defined as the harmonic source.

As mentioned before, a transformer's vector group plays a significant role in harmonic calculations. Therefore, to verify the precision of the developed tool, the comparison is made for two different vector groups, YNyn0 and Dyn5.

As it can be seen from the comparison shown in Table 2, values of deviation between developed and commercial tools are negligible, no matter the type or a transformer vector group. Both maximum and median differences between the results are not higher than 0.01%. Since the deviation is insignificant and it could be numeric, the results of the analysis and verification can lead to a conclusion that the developed tool can be used in harmonic analyses with different models of a transformer.

3.3. Test Case III

The networks presented in Test Case I and Test Case II are networks with only one or two voltage levels. As today distribution networks are moving towards smart, active distribution networks there is a possibility of reverse power flows and the propagation of PQ related problems from a lower voltage part to a higher voltage part of the network, i.e., the problems that occur in the distribution network can reflect in the transmission network. Therefore, the developed tool must be capable to work with more voltage levels. The network presented in Fig. 3 consists of 110, 10, and 0.4 kV nodes, two transformers, and lines connecting nodes. The loads are connected to both MV and LV nodes and are assumed to be harmonic sources.

As in the previous test case, both Type I and Type II analyses were made. For Type II, the results were compared for two different vector groups, YNyn0 and Dyn5. The comparison presented in Table 3 shows no significant differences in results of calculated harmonic voltages and THD_u that would make the developed tool unfit for planning and operation of power systems with multiple voltage levels. Even though the maximum deviation in some cases is slightly larger compared to the other cases and analyses, it can be determined as an outlier value, since the median deviation is not larger than 0.03% in the worst-case scenario. Current-related values do not present the problem since there is no difference in values calculated by the developed and commercial tools.

Fig. 1. Simple three-bus network.

3.4. Test Case IV

Networks presented in Test Case I, Test Case II, and Test Case III are defined as balanced distribution networks. LV networks are usually three-phase unbalanced networks and even though end-users can be single-phase or three-phase connected to the network, most of the end-users equipment is single-phase connected to the network. The benchmark CIGRE LV network defined by Strunz et al. [50] was modified and used for simulations and the verification of the developed tool. The network used for the verification in Test Case IV is presented in Fig. 4. Similar to previous cases, two vector groups were chosen, YNyn0 and Dyn5. Since the unbalanced harmonic calculation with the YNyn0 vector group is straightforward, the Dyn5 vector group is chosen since its model blocks the zero sequence current. Therefore, an implementation for that and similar vector groups is more challenging and additional functionalities must be implemented in order to keep the precision of the tool.

Table 4 shows the deviation between values calculated with the commercial tool and with the developed open source approach. The deviation between tools for the unbalanced analysis is higher compared to previous cases, especially when the vector group of a transformer is Dyn5 due to simplification in a transformer group modeling. However, even in the case of Dyn5, the value of median deviation is insignificant and does not impact the usability of the newly developed tool. When the tool is compared to Power Factory, the maximum deviation is significantly higher. However, this deviation is only an outlier value calculated for only one node, phase, and frequency. Additionally, the median deviation is lower and is only slightly higher than the deviation between the developed tool and NEPLAN. It is important to mention that every tool has its own characteristics, the precise definition of input data, and the mathematical model of the network. Due to the differences, it is possible that at some nodes or frequencies the deviations are larger. In spite of deviations, the results show no deviations in further use of the developed tool in harmonic analysis.

In all previous cases, only one harmonic source was connected to each phase or each node. Since the number of end-users with installed LC technologies is increasing and there are multiple harmonic sources connected to different phases and nodes there is a need for verification of the calculation in cases when there are multiple harmonic sources in the phase or node. A modified CIGRE LV network was used to verify the developed tool in the case when end-users have installed PVs, i.e., more than one harmonic source is connected to a certain node.

The results of the comparison presented in Table 5 are similar to the results of the analysis in which end-users did not have installed PVs. Even though the deviation occurs, the values are within acceptable boundaries and the difference in the results calculated with two tools does not significantly deteriorate the precision of the tool. When observing the values of comparison with the Power Factory commercial tool, the values are significantly higher than the values of comparison with NEPLAN. However, it is important to mention that such differences occur even when two commercial tools are compared. Each tool has its characteristics and to further decrease the deviation, a detailed mathematical model and the way of defining input data needed for the harmonic analysis should be investigated. Even though the maximum deviation is high, values of minimum and median deviation show that the developed tool is accurate and could be used in future analyses. This is important from the aspect of LV network operation, which is becoming more demanding since the number of end-users with installed

Table 1
Deviation between tools (absolute values) - Test Case I.

Harmonics-related quantity	Minimum deviation (%) - NEPLAN	Minimum deviation (%) - Power factory	Maximum deviation (%) - NEPLAN	Maximum deviation (%) - Power factory	Median deviation (%) - NEPLAN	Median deviation (%) - Power factory
U_h - Type I	0.00	0.00	0.00	0.00	0.00	0.00
THD_u - Type I	0.00	0.00	0.01	0.01	0.00	0.01
U_h - Type II	0.00	–	0.00	–	0.00	–
THD_u - Type II	0.00	–	0.01	–	0.01	–
I_h - Type I	0.00	0.00	0.00	0.00	0.00	0.00
THD_i - Type I	0.00	0.00	0.00	0.00	0.00	0.00
I_h - Type II	0.00	–	0.00	–	0.00	–
THD_i - Type II	0.00	–	0.00	–	0.00	–

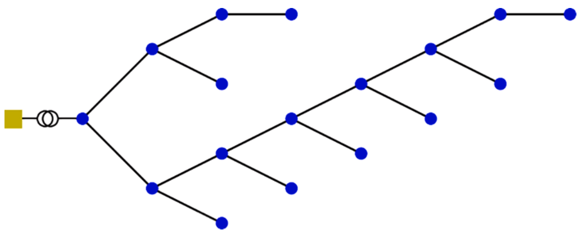

Fig. 2. Kerber synthetic network.

PVs or EV charging stations is increasing. The verification of cases in which more than one harmonic source is connected to a node is an important step in using the tool for further analyses of the power systems, especially LV networks with the increasing share of PVs, EVs, battery storage, and other LC units.

4. Application of the tool - Integration of DERs

The main motivation behind the development of the tool was enabling an easy and quick assessment of harmonic pollution in smart, active distribution networks. Since the share of EVs is constantly increasing and an installment of PVs is becoming more profitable, the number of end-users that decide to invest in LC units is growing. Both PVs and home EV charging stations are connected via power electronic devices to a network, and power electronic devices are one of the largest harmonic polluters in distribution networks. Besides LC units, already existing non-linear loads installed at the places of final consumption cause problems related to harmonic distortion. To additionally show the possibilities of the tool but also to show the importance of the development of such tools, a real-world case study is created in Section 4.

A network that represents Croatian urban LV feeder is defined and shown in Fig. 5. A case study is defined so that the impact of users with installed DERs on harmonic distortion can be realistically determined. Devices of every end-user connected to the network are considered as a harmonic source. Additionally, depending on the defined scenario, the different share of end-users have installed PVs and EV charging stations. Three different scenarios are created, mimicking the targets set by the EU for 2030 and 2050. In Scenario 1, none of the end-users have installed LC units. In 2030, 40% of energy should be produced from renewable energy sources [51]. Therefore, in Scenario 2 40% of end-users have installed PVs and EV charging stations at their households. A long-term plan defined in ACl [52] sets the target of energy production from RESs to more than 80%. Following the logic, Scenario 3 is defined as one in which 80% of end-users have installed PVs and EV charging stations.

Since every end-user is considered as a harmonic polluter, the residential harmonic spectra are created according to Niitsoo et al. [53], Mazin et al. [54]. The harmonic curves related to a PV production are made based on those defined in paper [55], while the harmonic spectra of an EV charging are based on the data collected from metering infrastructure installed in charging stations in Croatia. The power curve of an EV charging is created with the goal of minimizing the cost of participating in the day-ahead electricity market, while end-users consumption and PV production curves are created based on the data collected from smart meters. PVs and EV charging stations are single-phase connected to the network, and their connection phase is randomly selected since it

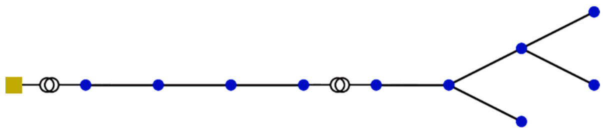

Fig. 3. HV-MV-LV test network.

Table 2
Deviation between tools (absolute values) - Test Case II.

Harmonics-related quantity	Minimum deviation (%) - NEPLAN	Minimum deviation (%) - Power factory	Maximum deviation (%) - NEPLAN	Maximum deviation (%) - Power factory	Median deviation (%) - NEPLAN	Median deviation (%) - Power factory
U_h - Type I	0.00	0.00	0.01	0.00	0.00	0.00
THD_u - Type I	0.00	0.00	0.01	0.00	0.01	0.00
U_h -Type II - YNyn0	0.00	–	0.01	–	0.00	–
THD_u - Type II - YNyn0	0.00	–	0.01	–	0.00	–
U_h - Type II - Dyn5	0.00	–	0.01	–	0.01	–
THD_u - Type II - Dyn5	0.00	–	0.01	–	0.00	–
I_h - Type I	0.00	0.00	0.00	0.00	0.00	0.00
THD_i - Type I	0.00	0.00	0.00	0.00	0.00	0.00
I_h - Type II - YNyn0	0.00	–	0.00	–	0.00	–
THD_i - Type II - YNyn0	0.00	–	0.00	–	0.00	–
I_h - Type II - Dyn5	0.00	–	0.00	–	0.00	–
THD_i - Type II - Dyn5	0.00	–	0.00	–	0.00	–

Table 3
Deviation between tools (absolute values) - Test Case III.

Harmonics-related quantity	Minimum deviation (%) - NEPLAN	Minimum deviation (%) - Power factory	Maximum deviation (%) - NEPLAN	Maximum deviation (%) - Power factory	Median deviation (%) - NEPLAN	Median deviation (%) - Power factory
U_h - Type I	0.00	0.00	0.00	0.00	0.00	0.00
THD_u - Type I	0.00	0.00	0.00	0.00	0.00	0.00
U_h - Type II - YNyn0	0.00	–	0.03	–	0.00	–
THD_u - Type II - YNyn0	0.00	–	0.03	–	0.03	–
U_h - Type II - Dyn5	0.00	–	0.10	–	0.01	–
THD_u - Type II - Dyn5	0.00	–	0.03	–	0.00	–
I_h - Type I	0.00	0.00	0.00	0.00	0.00	0.00
THD_i - Type I	0.00	0.00	0.00	0.00	0.00	0.00
I_h - Type II - YNyn0	0.00	–	0.00	–	0.00	–
THD_i - Type II - YNyn0	0.00	–	0.00	–	0.00	–
I_h - Type II - Dyn5	0.00	–	0.00	–	0.00	–
THD_i - Type II - Dyn5	0.00	–	0.00	–	0.00	–

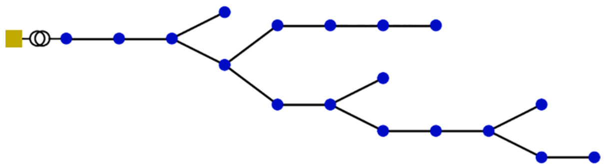

Fig. 4. Modified benchmark CIGRE LV network.

presents the realistic case in which end-users do not know the phase to which their devices are connected.

Harmonic analysis is made for one week period and the results of the analysis are shown in Fig. 6.

The analysis of the results shows a trend of increase of THD value with the integration of LC units. Even though the value of THD in phase A in Scenario 1 violates the limitation of 8%, a violation does not happen in more than 5% intervals, which is in accordance with different European standards and national grid codes [47,48]. Since it is expected that the share and installed power of LC units continues to grow, the

Table 4
Deviation between tools (absolute values) - Test Case IV.

Harmonics-related quantity	Minimum deviation (%) - NEPLAN	Minimum deviation (%) - Power factory	Maximum deviation (%) - NEPLAN	Maximum deviation (%) - Power factory	Median deviation (%) - NEPLAN	Median deviation (%) - Power factory
U_h - Type III - YNyn0	0.00	0.00	0.01	1.19	0.00	0.19
THD_u - Type III - YNyn0	0.00	0.12	0.00	0.29	0.00	0.21
U_h - Type III - Dyn5	0.00	0.00	0.27	0.85	0.13	0.09
THD_u - Type III - Dyn5	0.00	0.00	0.22	1.34	0.06	0.25
I_h - Type III - YNyn0	0.00	0.00	0.00	0.00	0.00	0.00
THD_i - Type III - YNyn0	0.00	0.00	0.00	0.00	0.00	0.00
I_h - Type III - Dyn5	0.00	0.00	0.00	0.00	0.00	0.00
THD_i - Type III - Dyn5	0.00	0.00	0.00	0.00	0.00	0.00

Table 5
Deviation between tools (absolute values) - Test Case IV - with connected PVs.

Harmonics-related quantity	Minimum deviation (%) - NEPLAN	Minimum deviation (%) - Power factory	Maximum deviation (%) - NEPLAN	Maximum deviation (%) - Power factory	Median deviation (%) - NEPLAN	Median deviation (%) - Power factory
U_h - Type III - YNyn0	0.00	0.00	0.02	1.12	0.02	0.22
THD_u - Type III - YNyn0	0.00	0.12	0.03	0.29	0.01	0.23
U_h - Type III - Dyn5	0.00	0.00	0.27	0.83	0.13	0.10
THD_u - Type III - Dyn5	0.00	0.00	0.20	1.46	0.06	0.17
I_h - Type III - YNyn0	0.00	0.00	0.00	0.00	0.00	0.00
THD_i - Type III - YNyn0	0.00	0.00	0.00	0.00	0.00	0.00
I_h - Type III - Dyn5	0.00	0.00	0.00	0.00	0.00	0.00
THD_i - Type III - Dyn5	0.00	0.00	0.00	0.00	0.00	0.00

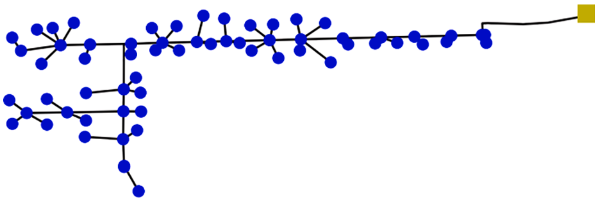

Fig. 5. Real-world LV circuit.

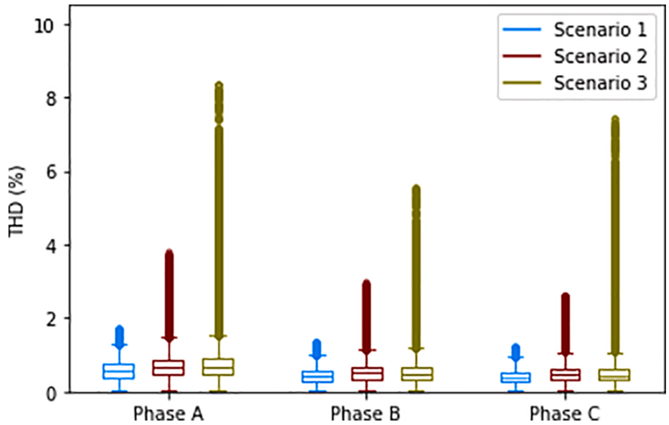

Fig. 6. Results of a real-world LV network harmonic analysis.

harmonics-related problems will only increase. This additionally emphasizes the importance of tools like the one presented in this paper, since it enables simple and quick calculations of complex power systems. The contribution of the paper is an implementation of the mathematical model and verification of the developed tool, and not finding a method that will help DSOs ins preventing and mitigating the problems related to harmonic distortion. However the open-source formulation, available at [39], simplifies further upgrades of the tool and potentially enables the integration of algorithms that will be used in the decrease or even mitigation of harmonic pollution.

5. Conclusions and future work

In order to overcome the intensive changes occurring due to power system decarbonization, the tools for the power system analyses need to be adaptable, expandable, and flexible. Having them openly available to a broader community creates opportunities for the development of new features and ideas and thus speeds up the transition toward a zero-emission society.

A detailed literature review identified that the existing open source tools often lack important technical analysis capabilities and mathematical explanations of how they are modeled and integrated. This hinders further development and analyses. To bridge this gap we develop an upgrade to an open source tool pandapower, an existing Python-based tool for analyses of steady-state power systems. The balanced and unbalanced harmonic analyses tool, soon to be implemented as a part of pandapower, is made freely available at [39], while technical and mathematical aspects of developing the tool are explained in the paper for the first time.

Three types of harmonic analysis were developed, two for balanced radial distribution systems, and one for three-phase unbalanced systems. The validation against commercial software shows negligible differences for the same defined test cases. After the verification, all benefits of the tool are shown on the additional test case that represents a real-world LV network.

Further upgrade of the tool includes full implementation in the pandapower library and the improvement of the accuracy, using more precise models of some elements, expansion with additional analyses, and verification of other, more complex test cases. Since the focus of the current version of the developed tool was put on distribution networks, which are in most cases operated radially, the mathematical model is not valid for the calculations of meshed networks. Further upgrades of the tool include an implementation of a method that is valid also for meshed grids. Backward-forward-based methods, which are planned to be implemented in future versions of the tool, are able to work both with radial and meshed grids but could also potentially contribute to increasing the tool's accuracy and speed, which is especially important for time-series analyses. Also, the developed tool can be used in numerous analyses, e.g., in determining the impact of a transformer vector group on PQ parameters, and in the planning and operation of smart distribution networks. An open source approach even enables the implementation of optimization or similar algorithms that will help DSOs in mitigating harmonics-related problems in distribution networks and guarantee success with further integration of LC technologies.

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CRediT authorship contribution statement

Tomislav Antić: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Leon Thurner:** Software, Validation, Data curation, Writing – review & editing. **Tomislav Capuder:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Visualization, Supervision, Funding acquisition. **Ivica Pavić:** Conceptualization, Methodology, Resources, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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A Comprehensive Analysis of the Voltage Unbalance Factor in PV and EV Rich Non-Synthetic Low Voltage Distribution Networks

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Abstract: With the development of technology and the decrease in prices, power systems are facing a strong growth in the number of end-users with photovoltaics (PVs), battery storages and electric vehicles (EVs). A penetration of low carbon (LC) technologies has an impact not only on the financial aspect, but also on parameters of the power quality (PQ) in the power system. Since most of end-users with renewable energy sources (RES) are connected to a low-voltage (LV) distribution network, there is a high number of single-phase loads and distributed generators (DG) that can cause unwanted effects in LV networks. According to standards, electric energy must be of a certain quality in order to avoid harmful effects on the power system, being both the network or the end-users equipment. One of the PQ parameters is the voltage unbalance. Voltage unbalance occurs in networks with the high share of single-phase loads and generators. Since most loads in households are connected to the only one phase, the voltage unbalance is constantly present in the network, even without LC technologies. Single-phase connected PVs, residential battery storages and EV charging stations can increase voltage unbalance in the system. This paper systematically analyzes a real-world LV network and different stages and shares of connected PVs, residential battery storages and EVs to different phases. The value of the voltage unbalance factor (VUF) is observed for one week in January and August in 10-min intervals. It is shown that connected systems can significantly increase the VUF and potentially cause negative impact on the equipment and the power system as a whole. In turn we analyze a three-phase connection of these new LC technologies and demonstrate how in all analyzed cases PQ values remain within boundaries defined by the EN 50160 and the IEC 61000-3-13.

Keywords: photovoltaics; residential battery storage; electric vehicles; low-voltage network; voltage unbalance factor

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1. Introduction

In the past years, a number of governments have become aware of the power system's impact on the environment. As part of the European Green Deal [1], the European Union (EU) proposed in September 2020 to raise the 2030 greenhouse gas emission reduction target to no less than 55% compared to 1999. The 2030 Climate and Energy Framework [2] has set key targets for 2030, that include at least 40% cuts in greenhouse emissions, 32% share for renewable energy and 32.5% improvement in energy efficiency. According to goals of 2050 long-term strategy [3], the aim of the EU is to have an economy with net-zero greenhouse gas emissions, i.e., to be climate-neutral by 2050. In order to accomplish that goal, governments are creating different instruments to stimulate end-users to invest in low carbon (LC) technologies and in that way, to contribute to accomplishing set goals.

Prices of LC technologies have been decreasing through years. Photovoltaics (PVs) have become one of the most important technologies for realizing a decarbonized power sector and sustainable energy supply. Over the last four decades, solar module prices have significantly fallen. The European Union's PV Report from 2019 [4] states that the average selling price of solar modules fell by 20% for each doubling of a production volume. From the end of 2009, the benchmark Levelized Cost of Electricity from PV system fell by more than 80%. The solar modules price reduction was driven not only by a technological development but also by market conditions and increasing electricity prices. The share of battery storages follows the growth of the share of renewables. According to [5], it appears that the capacity of battery storages will triple by 2030, if the share of renewables doubles. Similar as the solar modules price, the price of a residential battery storage has decreased through years and it is expected to continue decreasing in coming years. The total installed cost of a lithium-ion battery could fall by an additional 54–61% by 2030. Since batteries are the part of an EV that is the most influent on the price, the decreasing price of batteries should result in lower prices of EVs through years. With the decrease of prices and financial reliefs from governments, more end-users are able to invest in LC technologies. In that way end-users can reduce their electricity bill and help in accomplishing goals set by EU and other governments.

The integration of LC technologies potentially presents challenges for a distribution network. LC technologies are connected close to end-users and more end-users decide to invest in LC technologies and install them behind-the-meter. In this paper, we observe a passive distribution network, with less data know about the network, especially about the end-users' phase consumption. However, PQ boundaries are set and characteristic for both medium-voltage (MV) or low-voltage (LV) distribution network. The impact of behind-the-meter connection on the voltage unbalance parameter of the PQ on the MV and especially the LV network will be analyzed in this paper.

A high share of PVs in the MV or LV network can cause voltages with the magnitude that is higher than boundaries set by the grid code or the standards. [6] presents the optimal power flow (OPF)-based conservation voltage reduction (CVR) operation in distribution networks with the high share of PVs. The proposed CVR scheme takes the advantage of an advanced metering and communication infrastructures expected to be available to most DSOs in the near future. The optimization algorithm maximizes the customer's benefit and the network efficiency, while at the same time it minimizes the overall imported active power considering network constraints. Authors in [7] propose different techniques for an overvoltage prevention in LV networks: grid reinforcement, the application of active transformers, active power curtailment, reactive power management by PV inverters, demand respond and application of electrical energy storage systems (EESSs). This paper takes into the consideration the impact of a PV battery storage system, which is one of the ways to mitigate the overvoltage. Results in [8] show that it is possible to mitigate the overvoltage due to PVs and to increase the maximum allowable penetration level in New Zealand's LV distribution network are. Proposed methods are reactive power control with an appropriate voltage trigger level, with a power factor extended to 0.80, changing transformer tap-position to reduce the secondary voltage and increasing the voltage magnitude limit in New Zealand's LV network from 1.06 p.u. to 1.10 p.u., which is the limit in many countries, including Croatia, the county in which the tested LV distribution network from this paper is located. Since the share of PV systems and EVs can cause voltage problems, it is important to find methods to avoid potential problems in LV distribution network. Authors in [9] demonstrate that the overvoltage caused by PVs are slightly reduced by EVs and more importantly authors propose on-load tap-changing (OLTC) control method that is effective in managing voltage issues caused by a PV generation and an EV demand in LV networks.

Another potential problem that can occur with a growing share of LC technologies in the distribution network is the overhead lines and cables congestion. The focus of [10] has been identifying the potential of smart active power curtailment mechanisms to extend the market-based approaches to avoid network congestions. As a result of simulations, a mixed-integer programming (MIP)-based curtailment algorithm is proposed to select buses for a curtailment in a radial LV network. Studies in [11] investigated the EVs hosting capacity of different LV distribution networks in the UK. Analyses have shown that for some of tested networks problems start at the 40% penetration and it is mainly because of the transformer located at the substation, followed by thermal problems at the LV feeders. Ref. [12] presents a congestion forecast framework for visualization the probability for the network congestion and the voltage deviation in a distribution network with large number of both PVs and EVs. Uncertainties associated with the PV production, the load demand and the charging of EVs are taken into the consideration in case studies made in the paper. Results, based on Australian case study, indicate that the off-the-shelf (OTS) control of residential storage systems, meant to charge from PV surpluses, on average, reduces problems such as thermal utilization both in LV and high-voltage (HV) networks [13]. The OTS control faces challenges during problematic days (high PV production, low demand), when network problems cannot be mitigated. Authors in [14] propose the adaptive decentralized (AD) control strategy for residential battery storages to reduce both voltage and thermal issues whilst benefiting customers. The performance of AD control is compared against OTS control. Results show that AD control overcomes the limitations of OTS control and allows mitigating all voltage and thermal issues. The work in [15] proposes an adaptive centralized asset congestion management (ACACM) in PV-rich LV networks. ACACM uses available data, limited monitoring and based on irradiance measurements, it estimates total PV generation and demand to constantly calculate the maximum PV generation without causing the congestion of feeders and transformers.

With the continuous growth of share of LC technologies in distribution network, satisfying the power quality (PQ) is becoming more challenging task. Each of PQ parameters has boundaries that must not be violated. Analyses in [16] quantify variations of voltage, frequency and power factor on a monthly basis over a twelve-month period at the point of customer's connection at four households on different radial networks around Australia. The houses' location regarding the nearest network transformer, the houses' solar generation and the houses' load profile were examined to find correlation between these factors and the measured voltage variations. No direct correlation was found, suggesting that PQ variations measured at these households are attributable to non-PV causes, which is opposite to conclusions about the impact of PVs on overvoltage made in [6–9]. Authors in [17] have presented a quantitative analysis of PQ issues in the LV network with 68% of rooftop solar PV penetration. A case study investigated the effects, such as irradiance level, loading level and the time of the day, on the PQ indicators. In the case study that was made, total harmonic distortion (THD) and DC injection levels do not violate the statutory limits and the total demand distortion (TDD) values exceed the specified limits at several cases. Authors emphasize the importance of analyzing the cumulative effect on the system PQ by the non-linear loads and LC technologies connected to the network by inverters. In the research presented in [18] all of the measured PV systems had significantly different harmonic patterns, which makes difficult to propose simplified values for modelling without measuring and analyzing a greater number of devices. It is important to emphasize the difference between site measurements and the laboratory tests with controlled harmonic voltage conditions [19]. Comparing site measurements and laboratory tests indicated that the emitted harmonic currents depend strongly on the harmonic voltages in the AC-voltage. In order to avoid impermissible high order harmonics in power systems due to the operation of PV-generators, realistic test conditions have to be established and applied. In the power system with the high share of the renewable energy sources (RESs), battery storages are frequently used so that the end-user can optimize the operation of their hybrid RESs and battery storage systems. Optimal placement, sizing and operation of energy storage system (ESS) could possibly help avoiding the PQ problems, such as overvoltage, network congestion, harmonic distortion, voltage unbalance etc., caused by penetration of RESs [20]. Using the hybrid system with the adequate inverter provides a high-quality injected current from the PV array into a grid with a THD of less than 5% and stability of bus voltage against variation of the load [21]. The growing number of end-users with EVs and home chargers contribute to the voltage drop and THD that exceed the set boundaries. However, an optimal operation and a smart charging can help mitigating PQ problems. In the case study shown in [22], the replacement of traditional EV chargers with smart ones reduced the current THD from 51.6% to 1.8%. The same example shows that the voltage drop in the last house is 7.3%, which is the value lower than boundaries in most standards and national grid codes. Smart chargers used in the example allow mitigation of the issues in the distribution network and enable controlling the voltage and the current in batteries in order to maximize the batteries lifespan. PQ problems related to overvoltage and network congestion, but not to some other PQ aspects, caused by PVs and EVs could be solved by a strategy of the demand-side management that re-schedules charging loads of EVs using the deterministic programming algorithm based on historical data to maintain network constraints within their boundaries [23]. The proposed scheme is able to mitigate the impact of PVs and EVs on distribution networks by adjusting peak loads accordingly. As a result, the proposed strategy has capability to postpone upgrading needs of power grids, avoiding significant costs of the network reinforcement. Rapid voltage fluctuations caused by PV output fluctuations can result in visible light flickers. Simulations show that by the 2030, voltage fluctuations will no longer be major problems, and by the 2050, EVs will be able to limit fluctuations in residual loads to low values [24].

One of the biggest challenges in LV networks, related to PQ, is the voltage unbalance. Since the most of the household have single-phase loads, even the existing situation, without installed PVs, battery storages and EV chargers, results in voltage unbalance that exceeds the standard limits [25]. High number of single-phase LC technologies can increase the voltage unbalance in each node and in the entire LV network. Stochastic approach, in which the PVs penetration level and output power are considered as random input variables show that voltage unbalance factor (VUF) in certain time points of the day is higher than without installed PVs. In some observed time-points, VUF exceeds the standard limits [26]. According to EN 50160 [27] and IEC 61000-3-13 [28], the VUF may not exceed 2% (in some cases 3%) in 95% of 10 min interval values in one week. The PV system can also be connected to the network as a balanced three-phase source. When the PV system is connected to the network as a balanced three-phase source, the impact on the voltage unbalance cannot be neglected. It is shown that three-phase connection of the PV system helps reducing voltage unbalance. Simulations in [29] observed the installment of the PV system in only one node. It is shown that no matter how far the installed PV system is from the node in which VUF is calculated is, the VUF reduces. The impact of PVs on the VUF in the LV urban distribution reference network does not present the problem, since the VUF does not exceed the 2–3% boundaries [30]. Both in [29,30] authors observe the impact of only PV system on the VUF and the analysis are made for reference networks. However, the situation in the non-synthetic LV network could be different and there is need to analyze the impact of more LC technologies than only PV systems in cases that could potentially appear. Authors in this paper observe the impact of PVs, battery storages and EVs on the VUF in non-synthetic distribution networks.

Voltage unbalance can cause negative impact on equipment in the distribution network. Voltage unbalance can deteriorate the performance and reduce life expectancy of induction machines because of the temperature rise, losses and the decreased efficiency, it can negatively affect the AC adjustable speed drive system that are used to improve the motor operational efficiency. The negative sequence component voltage causes the negative sequence current occurrence which does not convey the energy, but it contributes to energy loss and reduces the capacity of distribution lines [31]. Because of the mentioned, and the influence of voltage and the current unbalance on other equipment in the power system, it is important to mitigate and reduce the voltage unbalance whenever possible. Some papers propose mitigation techniques in order to avoid harmful effects of the unbalance on the power system. When the phase of the connection is adequately selected, the hybrid system of PVs and ESS could possibly help the reduction of the VUF and the avoidance of the voltage unbalance [32]. Case study made in Brazil shows that it is imperative for PV integration studies to adequately model a single-phase PV system and to design suitable voltage control approaches based on reactive power compensation in order to avoid the voltage unbalance [33]. When using the hybrid system of a PV and a battery storage, it is possible to preform balancing via the same bus, which is the first choice and more efficient than balancing via the same phase but draws high ancillary batteries' current. When the capacity of the batteries is unavailable, balancing via the same phase and via the whole feeder compensate the deficiency [34]. Managing battery storages in a way to decrease the voltage unbalance does not present the economic value and the profit for end-users. Providing such services causes potential loss of profit for the end-user. Authors in [35] propose the intelligent and communication-based voltage profile regulating technique which is capable of simultaneously performing three steps: adjusting the voltage level by OLTC transformer, reducing the voltage unbalance by facilitating reactive power exchange and active power curtailment by the PV inverters. Because of the limitation of the PVs' injection or generation, prosumers do not achieve the profit as large as they potentially could. Phase load balancing (PLB) technique described in [36] presents the algorithm that consists of the identification of topology for the distribution network, uploading the input data and PLB procedure. The algorithm does not only analyze the voltage unbalance, but also the value of the current in the neutral current, which decreased 94% from the average value when using the proposed technique. Analysis of the LV distribution network made in [37] shows that despite demand being maintained, total losses calculated by the explicit four-wire approach increased by 4.1% for a 15% unbalance compared to a fully balanced system.

The authors in this paper model a specific real-world distribution network of an entire distribution area in Croatia, composed of the MV and LV elements, and provide a comprehensive analysis of the impact that the behind-the-meter low carbon (LC) technologies will have on VUF in LV networks under different shares and operating regimes. Here we defined four connection scenarios and four LC behavior scenarios (including optimization model of market driven prosumers) to systematically address the issue and draw conclusions.

The authors make a proposal for a unified balanced 3-phase connection rule for connection of behind-the-meter LC technologies to the LV network and, by preforming a comprehensive scenario analysis over all defined scenarios and options, we demonstrate how this rule successfully mitigates the VUF issues in the modelled real-world distribution network. The increase of total losses of 1% in Croatian networks is equal to around 120 GWh. If we assume that the average price of electricity is 50 €/MWh, the increase of 1% means that annual financial losses are increased for around 6,000,000 €. In case a unified balanced three-phase connection rule proposed in this paper is adopted, those financial losses could be avoided. Some of other approaches for reducing the voltage and current unbalance proposed in [31] are: imposing regulation and standards with respect to equipment and transmission line construction and adopting standards on acceptable levels of current and voltage unbalance, structural modifications of single-phase loads—on both utility and customer sides, integration of single-phase voltage regulators and balancing compensators. Even though proposed approaches are efficient, they require the investment in the equipment, which presents additional cost to the system operator.

The contributions of this paper are:

(1) Analysis of the impact of different LC technologies on the voltage unbalance in the non-synthetic LV distribution network. Most of the papers that analyze the same problem take into the consideration only PVs or the combination of PVs and battery storages, which are often used for decreasing the voltage unbalance [34]. In that way end-users lose the opportunity to maximize their profit. In this paper, the additional LC technology that was analyzed is EV charging station. The existing literature is analyzing the EV charging only from the perspective of relieving voltage and congestion problems [11,12] and not because of the impact that single-phase charging stations have on the voltage unbalance. Further, the existing literature body does not analyze different operational nodes and their impact on the voltage unbalance.

(2) The authors in this paper analyze the voltage unbalance according to General Summation Law described in IEC 61000-3-13 [28], meaning that the voltage unbalance was not analyzed only in the end-user's node, but also in the entire observed LV network. Authors in [26] analyze voltage unbalance in different time periods, while in [29] the voltage unbalance in only one node is analyzed. In [29,30] authors make the analyses in the reference synthetic network. Voltage unbalance in this paper was analyzed both from the perspective of the value in the non-synthetic LV distribution network and the occurrence of the VUF thresholding the limitation set by standards [27,28].

(3) A unified balanced 3-phase connection rule for connection of behind-the-meter LC technologies to the LV network is proposed in this paper. Both in [29,30] authors propose and encourage the three-phase connection, but they do not include the analysis of the impact of battery storages and EVs. Other papers propose methods that can reduce the voltage unbalance with the hybrid system of battery storage and PV, in case when the connection phase is adequately selected. Analysis made in this paper shows that no matter the selection of connection phase, voltage unbalance occurs even in the situation when the hybrid system is used. Authors in [35,36] propose intelligent and communication-based techniques and algorithms in order to reduce voltage unbalance. Since the voltage can be changed by injecting or withdrawing energy, it is not possible that end-users maximize their profit, unless they are stimulated to change the consumption or reduction power at the node. The method proposed in this paper does not affect the profit and the comfort of the end-user, since they are not asked to participate in the voltage unbalance reduction.

The rest of the paper is organized as follows: Section 2 briefly introduces the methodology; the description of the LV network, load and PV profile, the optimization of charging and discharging of battery storages and charging of EVs. Section 3 presents results of simulations and the comparison between them. Finally, Section 4 highlights the conclusions and the future work.

2. Methodology

In this section, the modelling of the distribution network for analyzing the voltage unbalance is presented. The analyzed distribution network consists of the network feeder that represents the rest of the MV network, the MV node, the MV/LV transformer, 120 LV nodes and 118 LV overhead lines and underground cables. The detailed information about the MV/LV transformer is shown in Table 1. The average length of the LV overhead lines and cables is 0.05 km and the total length is 5.86 km. The observed LV network is modelled with 11 different types of overhead lines and cables. Each type is defined with R1 (Ω/km), X1 (Ω/km), R0 (Ω/km), X0 (Ω/km) and maximum current (A).

Table 1. Transformer's parameters in the observed LV network.

U_1 (kV)	U_2 (kV)	u_{kr1} (%)	u_{kr0} (%)	S_n (MVA)	P_{Fe} (KW)
10	0.4	3.86	3.86	630	0.9

The details about nodes in the observed network are shown in Table 2. Table 2 defines type of each node, MV and LV busbar, which are MV and LV node of the transformer in the 10/0.4 kV substation, end-user's node, which represents the node in which end-user is connected and has installed LC technologies and electric switch cabinet, which is the node that has no consumption or production but is only used as a node from which overhead lines or cables go to the end-users. The power demand changes depending the phase and the time, but in the worst-case scenario maximum power of the entire LV network is 671 kW. This occurs only if all three phases are maximum loaded in the single-phased end-user nodes and all three-phase connected end-users must also consume maximum power. It needs to be noted that this is not a realistic case.

Table 2. Nodes in the observed network.

Nodes	Type
TS MV	Substation MV Busbar (10 kV)
TS	Substation LV Busbar (0.4 kV)
LV1–LV103	End-user's node (0.4 kV)
KRO1–KRO15	Electric switch cabinet (0.4 kV)

The elements of the LV distribution network that are causing the voltage unbalance are loads, PVs, battery storages and EV charging stations. In the initial case, only the impact of households' loads was observed. The results of the initial case are compared to different cases, with PVs, battery storages and EV at 20%, 40%, 60% and 80% of nodes.

The LV distribution network is modelled using geographic information system (GIS) data. GIS data are becoming more important and are often used in a distribution network modelling [38] and distribution network analyses, e.g., distribution networks with a high penetration of PVs [39] and future distribution networks [40]. Figure1presents the analyzed LV distribution network, that is the part of the distribution network in Croatia, shown in QGIS. Using the attribute table in QGIS, it is possible to find more detailed information about nodes and lines. Information about nodes is the name and the type of each node. Types define the size of an end-user at each node, e.g., hospital which has three-phase loads, houses with single-phase loads, buildings with more than one household, electric switch cabinets that present the node from which cables go to each end-user etc. Information about lines is the length of each line, type of the line, from which is possible to find values of the resistance, the reactance, the maximum current and the node at the beginning and the end of the line.

Figure 1. Modelled LV distribution network.

2.1. Load Profile

Since the real-time measurements are not publicly available, the load profile curve was created with the help of Load Profile Generator [41]. The time-dependent load profile curve on 10 min basis is used. Two weeks were observed, 13–19 January 2020 and 1–7 August 2020. Besides the load profile curve, the installed power and the power factor for each node are known. It is implied that the installed power of each phase at the node is same, e.g., node LV54 presents a three-phase house and the maximum power of each phase is 2 kW.

Since the most of households have loads that are single-phase connected to the network, values of loads connected to the node are not the same. Therefore, it is assumed that at each node one phase is loaded with 100%, one with 85% and one with 70% of the load profile curve shown in FiguresA1andA2in AppendixA. These curves are used for all nodes in which loads are single-phase connected to the network. In some nodes, e.g., in node LV2, big and important consumers, such as hospitals, are connected to the LV network. Loads in those nodes are symmetrically, three-phase connected to the network, i.e., the value of the load in each phase is the same.

2.2. PV Production Profile

PV production profile curve is created from the rooftop measurements. The value of production power in each time period is divided by the maximum production power. The time-dependent PV production profile curves on 10 min basis are created the from real data, i.e., rooftop measurements. The maximum PV production power is known in each node with the installed PV. Load profile curves for each day in January and August are shown in FiguresA3andA4. The PV production profile curve values multiplied by the maximum power at each node give the value of the PV production at each node with the installed PV, for every time interval in observed week.

2.3. Battery Modelling

Deciding the optimal capacity of installed PV and residential battery storage system for making the profit could be a problem for end-users. It is expected that with the minorizing feed-in payments in the future, an optimal PV battery system size is going to shrink to a small-scale PV battery system [42]. Studies compare different energy management strategies, such as: optimization-based approaches, machine learning approaches and rule-based heuristic approaches [43]. Due to modelling assumptions, authors emphasize the necessity of taking with caution conclusions about the best energy management strategy. To unlock the volume of services provided by aggregators, authors in [44] explore the use of day-ahead time-varying active power export limits for each prosumer considering the constraints of the corresponding network.

The battery in this paper is modelled using two different optimization-based methods. In the first method, the objective function is minimizing the deviation between consumption and production at each node and the second is maximizing the profit from selling the energy on the energy market.

2.3.1. Method 1

In Method 1, the goal is to minimize the deviation between the consumption and the production. A residential battery storage can be charged both from PV production and from energy bought in the energy market. Residential battery storage can be discharged satisfying the demand at the node and selling the energy on the energy market. Method 1 does not take into consideration market prices, i.e., the battery will not charge because the price on the market is lower, it will charge because the production at the node is higher than the consumption. Depending on the characteristic of the end-user (single-phase or three-phase loads), VARTA [45] and Tesla Powerwall [46] batteries are used. Charging power, discharging power and state of charge are different, depending on the battery that is used at the node. State of charge (SOC) of the residential battery storage at the first and the last time period is set to be zero.

Equation (1) puts the constraint on the charging power of the battery for every node and at every time period, while Equation (2) puts the constraint on the discharging power. Equation (3). limits the state of charge of the battery:

$$P_{n,\,t}^{ch,bat} \leq P^{ch,bat\ max} \tag{1}$$

$$P_{n,t}^{dis,bat} \leq P^{dis,bat\ max} \tag{2}$$

$$SOC_{n,t}^{bat} \leq SOC^{bat\ max} \tag{3}$$

Equations (4)–(6) define same constraints as Equations (1) and (2), with addition of condition that defines that the battery cannot be charged and discharged at the same time:

$$P_{n,\ t}^{ch,bat} \leq x_{n,t}^{ch,bat} \cdot P^{ch,bat\ max} \tag{4}$$

$$P_{n,t}^{dis,bat} \leq x_{n,t}^{dis,bat} \cdot P^{dis,bat\ max} \tag{5}$$

$$x_{n,t}^{ch,bat} + x_{n,t}^{dis,bat} \leq 1 \tag{6}$$

Equations (7) and (8) define the difference between the consumption and the production at every node and at every time period. Equation (9) defines the SOC at every node and every time period, regarding the SOC in the previous hour, charging and discharging power. The power of charging and discharging is multiplied by τ in order to convert power to energy:

$$P_{n,t}^{delta} = P_{n,t}^{load} - P_{n,t}^{PV} + P_{n,t}^{ch,bat} - P_{n,t}^{dis,bat} \tag{7}$$

$$P_{n,t}^{delta} = P_{n,t}^{delta,pos} - P_{n,t}^{delta,neg} \tag{8}$$

$$SOC_{n,t}^{bat} = SOC_{n,t-1}^{bat} + P_{n,t}^{ch,bat} \cdot \tau - P_{n,t}^{dis,bat} \cdot \tau \tag{9}$$

Equation (10) represents the objective function, which has the goal of minimizing the total deviation between the consumption and the production at every node and every time period.

$$\text{Minimize } \sum_{n=1,\ t=1}^{N,T} \left(P_{n,t}^{delta,pos} + P_{n,t}^{delta,neg} \right) \tag{10}$$

FiguresA5andA6in AppendixAshow the charging and the discharging profile when the battery is modelled with the logic of self-sufficiency, both for January and August.

2.3.2. Method 2

In Method 2, the goal is to minimize the cost from participating on the DA market. Unlike the optimizing algorithm in Method 1, DA prices will be considered during battery charging and discharging cycles. End-user can both buy and sell on the electricity market. DA prices [47] are prices from CROPEX, the Croatian electricity market. As in Method 1, VARTA and Tesla Powerwall batteries are used, depending on the characteristic of the end-user (single-phase or three-phase loads). Charging power, discharging power and state of charge are different, depending on the battery that is used at the node. State of charge (SOC) of the residential battery storage at the first and the last time period is set to be zero.

Equations (11)–(18) are same as Equations (1)–(7) and Equation (9) described in Method 1.

$$P_{n,\ t}^{ch,bat} \leq P^{ch,bat\ max} \tag{11}$$

$$P_{n,t}^{dis,bat} \leq P^{dis,bat\ max} \tag{12}$$

$$SOC_{n,t}^{bat} \leq SOC^{bat\ max} \tag{13}$$

$$P_{n,\ t}^{ch,bat} \leq x_{n,t}^{ch,bat} \cdot P^{ch,bat\ max} \tag{14}$$

$$P_{n,t}^{dis,bat} \leq x_{n,t}^{dis,bat} \cdot P^{dis,bat\ max} \tag{15}$$

$$x_{n,t}^{ch,bat} + x_{n,t}^{dis,bat} \leq 1 \tag{16}$$

$$P_{n,t}^{delta} = P_{n,t}^{load} - P_{n,t}^{PV} + P_{n,t}^{ch,bat} - P_{n,t}^{dis,bat} \tag{17}$$

$$SOC_{n,t}^{bat} = SOC_{n,t-1}^{bat} + P_{n,t}^{ch,bat} \cdot \tau - P_{n,t}^{dis,bat} \cdot \tau \tag{18}$$

Equation (19) represents the objective function of Method 2, which has the goal of minimizing the cost of buying the electricity, i.e., maximizing the profit of selling the electricity on the DA market:

$$\text{Minimize } \sum_{n=1,\ t=1}^{N,T} P_{n,t}^{delta} \cdot p_t^{DA} \tag{19}$$

FiguresA7andA8in AppendixAshow the charging and the discharging profile when the battery is modelled as if prosumers are active DA market participants, both for January and August.

2.4. EV Charging Cycle Modelling

All end-users with installed PVs and residential battery storages, could potentially have EV charging stations. It is supposed that all end-users have the same Nissan Leaf Battery Electric Vehicle [48]. Similar as finding the optimal charging and discharging cycles of residential battery storages, optimal charging cycles for the battery in the EV are decided using the optimizing algorithm. The EV charging curve is price-based determined and it is same for all end-users. The battery can charge between 5:00 P.M. and 6:00 A.M. It is supposed that in these hours, end-users are at home, and it is possible for them to charge their EVs. Also, for each day in the week, the minimum charging capacity of the EV is different, depending on the wanted driving range.

Equations (20) and (21) define the maximum and the minimum charging power of the battery in the EV. Equations (22) and (23) put constraints on the SOC of battery in the EV, i.e., they define that the capacity of the battery must be between the minimum and the maximum capacity. Minimum capacity is defined by the end-user and the maximum capacity is defined by technical parameters of the EV:

$$P_t^{ch,EV} \leq P^{ch,EV\ max} \tag{20}$$

$$P_t^{ch,EV} \geq \ P^{ch,EV\ min} \tag{21}$$

$$\sum_{t=1}^{T} P_t^{ch,EV} \cdot \tau \leq SOC^{EV\ max} \tag{22}$$

$$\sum_{t=1}^{T} P_t^{ch,EV} \cdot \tau \geq SOC^{EV\ min} \tag{23}$$

Equation (24) represents the objective function of EV charging cycles. The goal of the objective function is to minimize the cost of the electricity bought on the DA market.

$$\text{Minimize } \sum_{t=1}^{T} P_t^{ch,EV} \cdot p_t^{DA} \tag{24}$$

TablesA1andA2in AppendixAshow time periods during which EVs are charged, for one week in January and one week in August. In almost every time period, EV is charging with the maximum power. Because of the constraints, the EV is charging only during the night hours. The curve is not the same for every day because the needed capacity of the battery is different. The capacity is determined by the capacity at the end of the day and the needed driving range in the following day.

TableA1shows hourly charging power for each EV's during each day of the observed weeks. These values come as results of the optimization model presented with Equations (20)–(24) for each 10 min interval. The assumption made in the model is that EVs are only charged in the afternoon hours after the end-user arrive at their households, i.e., during the night. For this reason, only those periods are shown in TableA1. Because of the maximum charging power and the capacity of the battery, the EV is charged with 3.6 kW during most time intervals. During time periods that are not shown in TableA1, the value of charging power is 0 kW, i.e., the EVs are not charging. It is assumed that the behavior of all end-users is the same, meaning that the constraints defining charging periods are the same for every end-user with the EV.

The logic of EV charging is the same for January and for August. TableA2shows the values for EV's charging in August week.

3. Results

The aim of the paper is to provide a large set of scenarios and through a comprehensive analysis draw general conclusions on the impact of different LC technologies on PQ aspects in LV distributions networks. In the line with this, we created four scenarios and for each of the four scenarios, we performed four case studies. Each scenario and case study are simulated and analyzed over a period of one week in January and one week in August in time steps of 10 min. We have defined the following scenarios:

- Phase L1—Scenario 1
- Random phase—Scenario 2
- All three phases (three-phase)—Scenario 3

In Scenario 1, all LC technologies are connected to the phase L1 in every node. In Scenario 2, the phase on which LC technologies are connected, is randomly chosen for each node. In Scenario 3, we analyzed the three-phase connection of LC technologies in every node. The impact of the use of different technologies is shown in this paper. Observed cases are:

- PVs–Case 1
- PVs and EVs—Case 2
- PVs, batteries (Method 1) and EVs—Case 3
- PVs, batteries (Method 2) and EVs—Case 4

In Case 1, PVs are the only used LC technology. In Case 2 end-users have PVs and the EV charging station. In Case 3 and Case 4, PVs, battery storages (Method 1 and Method 2) and EV charging stations are connected to each observed node. The referent, or benchmark case (Initial scenario) is the one where no LC technologies are connected to the distribution network, only single-phase and three-phase loads. Simulations for each case and scenario are made for the share of LC technologies at 20% (Share 1), 40% (Share 2), 60% (Share 3), 80% (Share 4). Overall, this means that the entire distribution network described above is analyzed over 128 weekly 10 min simulations.

Asymmetrical Load Flow calculations were made using NEPLAN V558 software tool. As the results of analysis, the voltage magnitude and the voltage angle at each phase and each node are calculated. To determine the VUF, it is necessary to calculate the positive-sequence (Equation (25)) and the negative-sequence (Equation (26)) component of the voltage:

$$U_{positive} = \frac{1}{3}\cdot\left(U_a + a\cdot U_b + a^2\cdot U_c\right) \tag{25}$$

$$U_{negative} = \frac{1}{3}\cdot\left(U_a + a^2\cdot U_b + a\cdot U_c\right) \tag{26}$$

$$a = 1\angle 120^\circ \tag{27}$$

$$a^2 = 1\angle 240^\circ \tag{28}$$

The VUF is defined as the ratio of the modulus of the negative-sequence to the positive-sequence components of the voltage at fundamental frequency, expressed as percentage [28]:

$$VUF_n[\%] = \frac{|U_{negative}|}{|U_{positive}|}\cdot 100 \tag{29}$$

According to the Croatian Grid Code [49], the VUF at the LV node where the end-user is located must not exceed the value of 0.7% at 95% of 10 min interval in one week. General summation law is adopted for the distribution network with a large number of unbalanced installations (e.g., a number greater than 10 is considered), or when the unbalance changes randomly with time [28]. Since both conditions are satisfied in the tested network, General summation law was used to determine if the VUF in the LV network exceeds boundaries. Equation (30) defines the general summation law for resulting VUF:

$$VUF[\%] = \sqrt[\alpha]{VUF_n[\%]^{\alpha}} \tag{30}$$

$$\alpha = 1.4 \tag{31}$$

3.1. Case 1

Figure 2a–d present the change of the value of the VUF with the increase of LC technologies penetration in case where end-users only have PVs on the rooftop. Comparing the results, the value of the VUF in August is generally higher than the value in January. It can be explained with the higher power of production from PVs in summer months. Therefore, the difference between total loads (consumption and production combined) of each phase is more significant in summer months. Also, the interquartile interval in August is larger compared to one in January. Because of that, there are a lot more outlier values in January. Those values must be considered because extreme scenarios and their occurrence is possible.

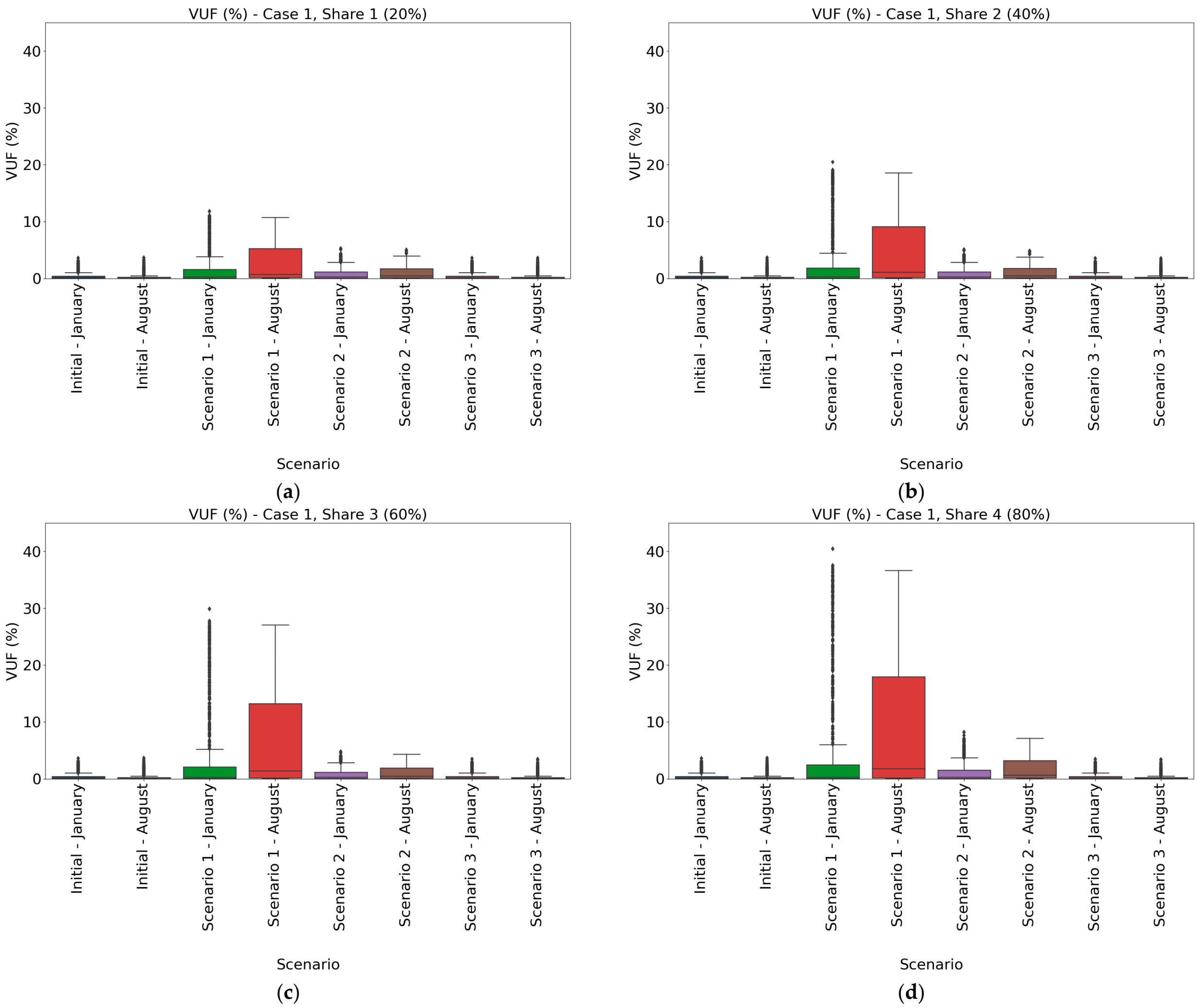

Figure 2. VUF (%)—Case 1; Share 1–Share 4; January, August.

Comparing the results of different scenarios, the worst situation is in Scenario 1. In this scenario, PVs are always connected to same phase, phase L1. The range of the resulted VUF values is larger than in Scenario 2 and Scenario 3. Scenario 2 considers connecting

PVs to a different phase at each node and that solution is preferred from the DSO's perspective because of the avoidance of possible problems with the distribution network and the equipment. Besides the Initial scenario, the best scenario is one in which PVs are symmetrically connected to all three phases (Scenario 3). In that scenario results are similar as ones in the Initial, and the occurrence of problematic values of the voltage unbalance is not as often as in other scenarios. A three-phase connection of PVs is the possibility that should be encouraged by DSOs because the probability of negative impacts is seldom compared to a single-phase connection, when values are significantly higher, which leads to an unsatisfying performance of some of the equipment and of the distribution network as a whole.

Figure3a–d present how many ten-minutes intervals during one week are larger than the threshold value of 2%. In Initial scenario and Scenario 3 there is no problem with the voltage unbalance, i.e., the value of the VUF is less than 2% in more than 95% of 10 min intervals, which satisfies the standard IEC 61000-3-13 [28]. Comparing Initial and Scenario 2, the unallowed VUF in the observed LV network appears more often in January compared to August. However, in all other scenarios, unallowed VUF appears more often in August. In Scenario 1 unallowed voltage unbalance occurs in more than 20% in January and in little less than 40% in August when the penetration of PVs is lowest and larger than 40% when penetration is higher.

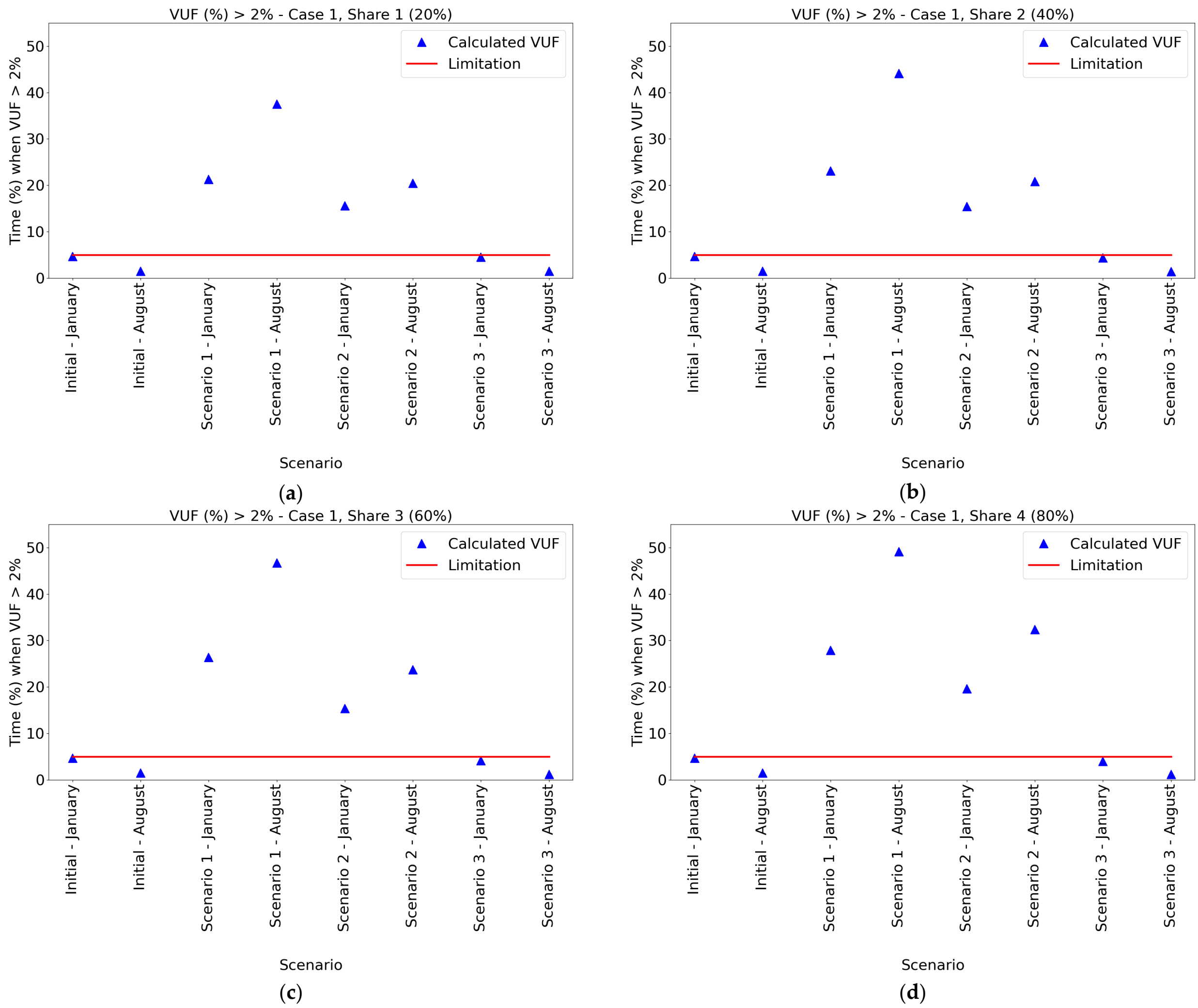

Figure 3. VUF > 2%—Case 1; Share 1–Share 4; January, August.

Results of Scenario 2 show that changing the phase on which PVs are connected benefits the system, i.e., the occurrence of VUF above the threshold value is not as often as in scenarios when PVs are connected to the same phase in each node.

3.2. Case 2

Figure4a–d show results of the analysis made in Case 2. End-users in Case 2 besides PVs have EV charging stations and every one of them charges EVs during evening and early morning, when end-users are at home. It is supposed that every end-user drives Nissan Leaf. Therefore, the charging power curve is same for every end-user.

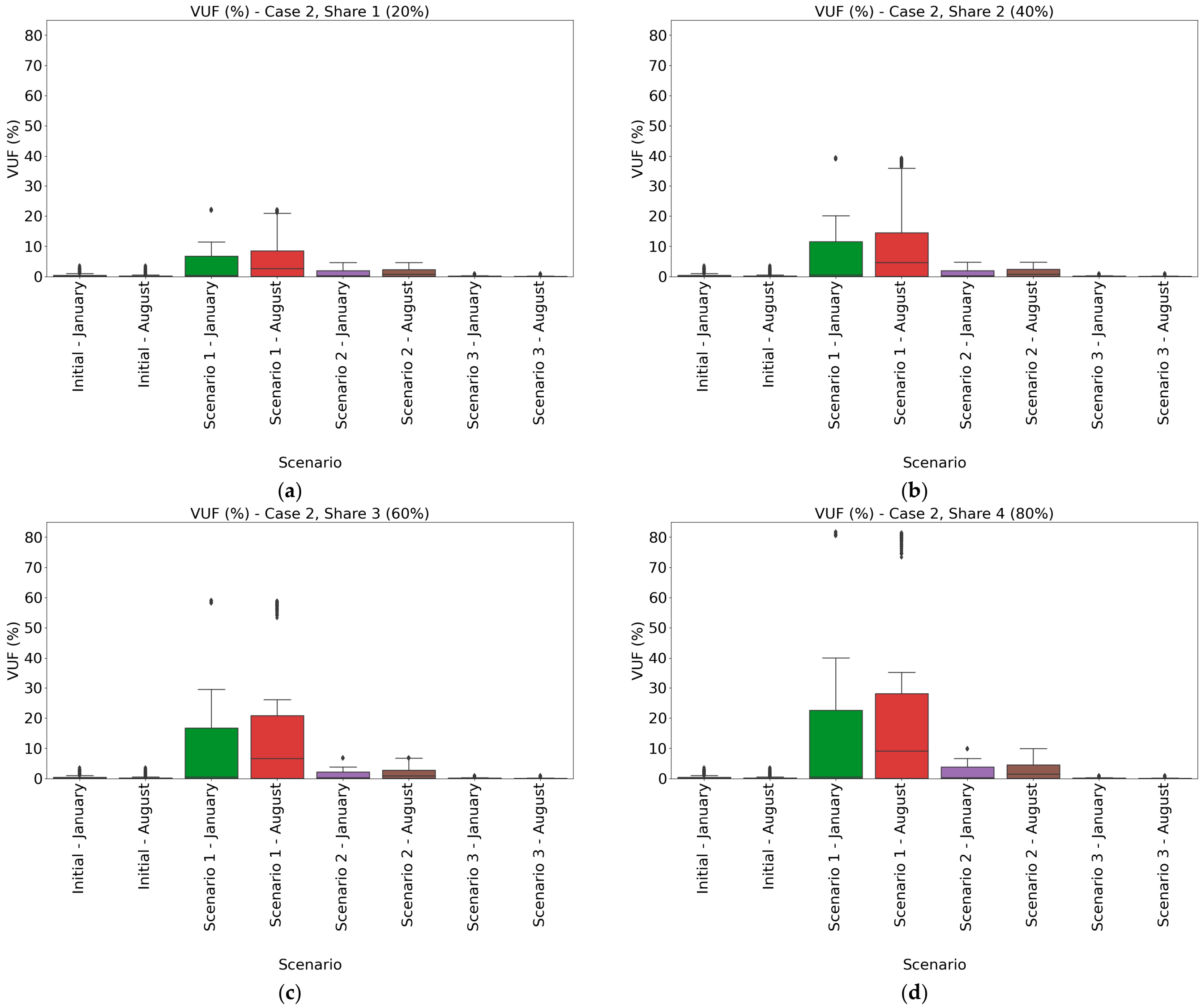

Figure 4. VUF (%)—Case 2; Share 1–Share 4; January, August.

Comparing results of Case 2 to the previous case shows that charging EVs at home presents more problems from the network's perspective than only a PV does. Interquartile range of the VUF values is larger than ranges in Case 1. Additional problems present outlier values, values that considerably differ from values in the interquartile range. Those values present time intervals in which difference between phase voltage magnitudes is larger than in the most of observed intervals. For example, results of Case 2, Share 4 in January and August show that for Scenario 1 most of the VUF values are not larger than 40%, but extreme values go even beyond 80%.

As one can notice in Scenario 1, placing the PVs and the EV chargers on the same phase causes more unbalance in the LV network compared to changing the phase of connection at each node. Interquartile range in Scenario 2 is smaller compared to ranges in Scenario 1. Even the outlier values are not as high as in Scenario 1.

Generally, values of VUF are larger in August than in January. Even though the interquartile range in January and August for share of 80% (Share 4) is similar for both months, there is a lot more outlier values in August. Since the EV charging curves look similar for both January and August, results in Case 2 lead to the conclusion that a PV has the dominant influence in the difference between two months.

Figure 5a–d show the percentage of time in which the summed VUF values in the LV network are higher than 2% for Case 2.

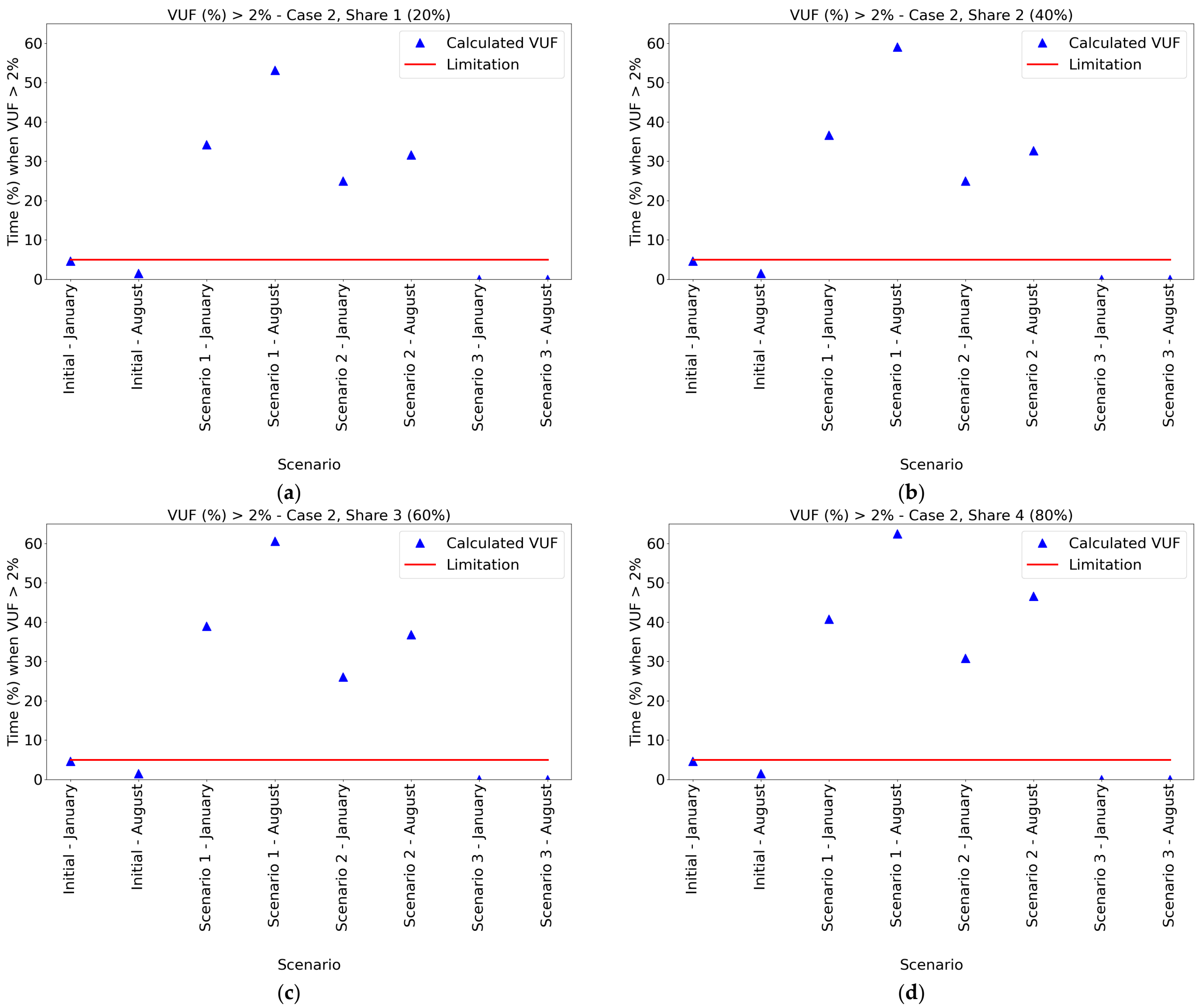

Figure 5. VUF > 2%—Case 2; Share 1–Share 4; January, August.

Once again, connecting the LC technologies on the same phase at each node presents a potentially large problem for the system. Depending on the share and the month, the VUF thresholding the limit can occur in more than 60% of 10 min intervals in one week (Scenario 1, Share 4, August). Even in Scenario 2, when the connecting phase changes, the unallowed VUF values can occur in almost 50% of the observed week (Share 3, Share 4, August). Knowing the negative impact that the unbalance can have on the equipment and the LV network, end-users should be encouraged to symmetrically distribute PVs and EV charging stations to all three phases, i.e., to install PVs and charging stations three-phase. No matter the share, results in Scenario 3 show that a three-phase placement of LC technologies additionally reduce the time in which the unallowed VUF is present in the network.

3.3. Case 3

Analysis in Case 3 was made for the end-user that has hybrid system consisting of the PV, the EV charging station and the battery with the charging and the discharging power curve created with Method 1 (Section2.3.1). Figure6a–d present results of the analysis. Comparing values to those in Case 2, when end-user did not have the battery, shows that using the battery storage could decrease maximum values of the VUF in the LV network, e.g., maximum values of the VUF in Case 3 do not exceed 60%, while values as high as almost 80% occur in Case 2.

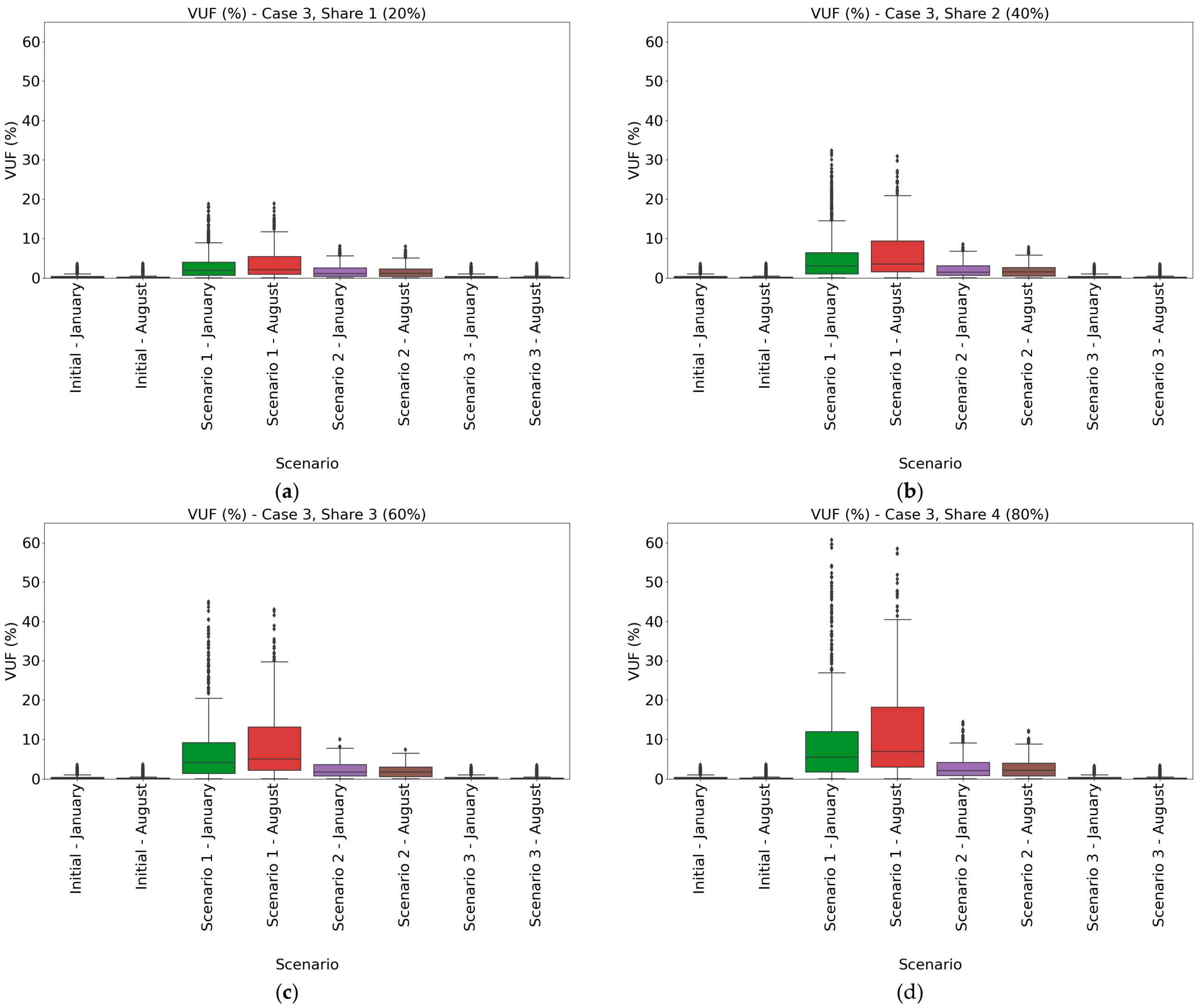

Figure 6. VUF (%)—Case 3; Share 1–Share 4; January, August.

The difference between January and August is not as significant as in Case 1. Since the battery is used for deviation minimization, increased generation power in the August is reduced with the battery storage. As in all previous cases, Scenario 2 shows that when end-users decide to single-phase connect their LC technologies, they should be connected to a different phase at every node. No matter the month, scenario and share, the maximum value of the VUF does not exceed 20%. Results show that the difference between Initial and Scenario 3 is not as significant as difference between Initial and scenarios in which hybrid system were connected single-phase. Values of the VUF that are thresholding limitations do not occur often and therefore reduce the negative impact.

Figure7a–d show how often does the VUF value threshold the limit set by the standard [28] in Case 3. Despite the fact that the addition of the battery storage does not significantly impact on the VUF value or even decreases them (compared to Case 2), frequency of the unallowed VUF occurrence is higher in Case 3 than in above mentioned Case 2. While the month, share and scenario in which frequency is the highest, remains the same as in previous cases, results of the analysis in August, Scenario 1, Share 4, shows that the unallowed VUF values occur in more than 80% of the observed weekly 10 min intervals.

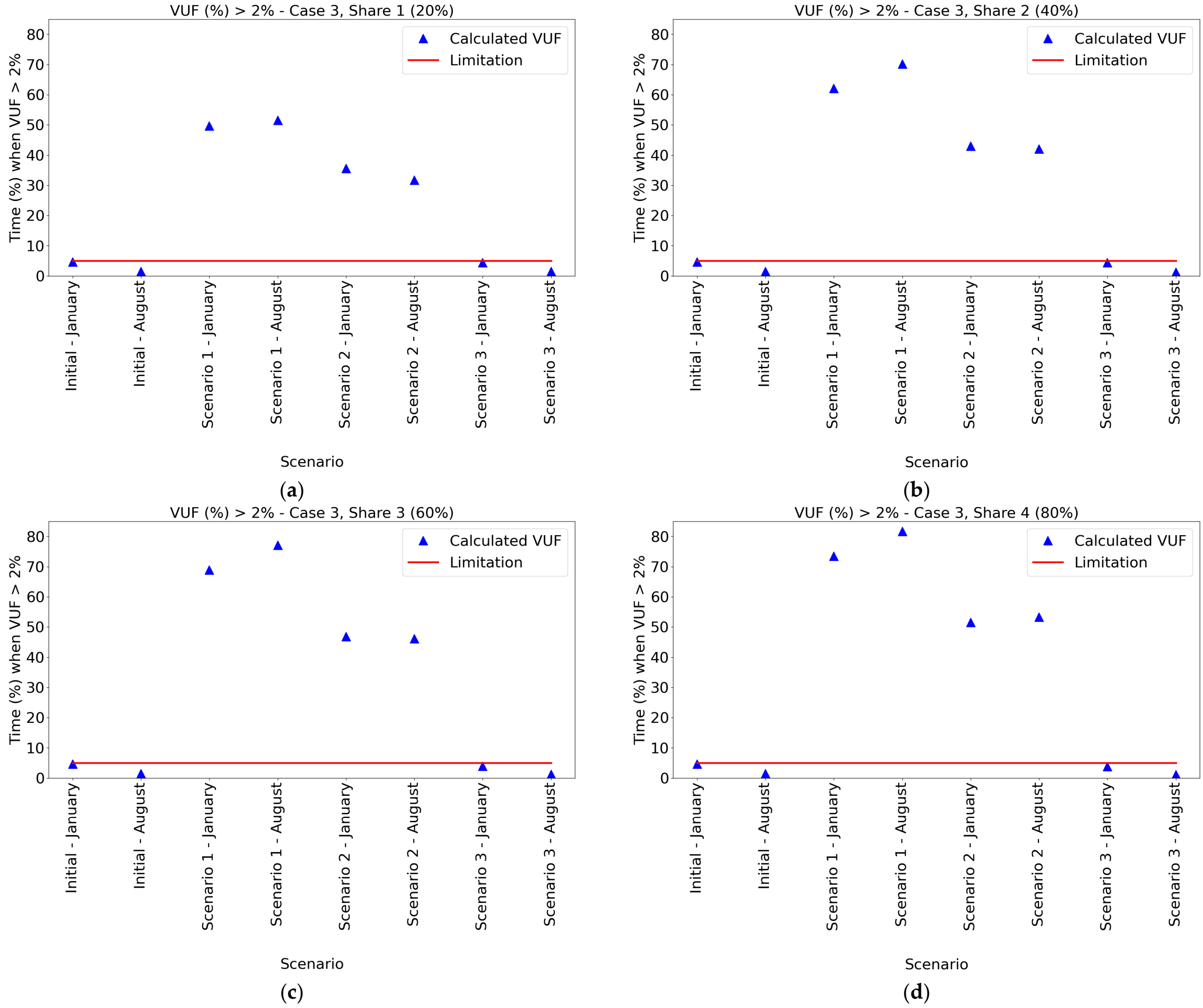

Figure 7. VUF > 2%—Case 3; Share 1–Share 4; January, August.

Comparing the results of Case 2 to ones of Case 3 shows that decreasing the VUF values does not inevitably mean decreasing the frequency of the occurrence of the VUF values that threshold limitations. In all scenarios and for all shares, a time when the VUF values are higher than 2% is higher in Case 3 than in Case 2. The exception is Scenario 3 in which LC technologies are three-phase connected to the node. Despite the share and the month, three-phase connection of the LC technologies does not present problems related to the unallowed VUF. In order to decrease the impact of single-phase loads, DSOs should encourage end-users to connect PVs, battery storages and EV charging stations symmetrically to all three phases, so that end-users become the solution and not the cause of the LV network problems.

3.4. Case 4

Figure 8a–d show results of the analysis made in Case 4. Results show that end-users that have battery modelled as prosumers are active DA market participants cause voltage unbalance with values that are slightly higher than those in Case 4 (self-sufficient end-users). Maximum values are not as high as extreme ones in Case 2 when end-users with only the PV and the EV charging station cause the voltage unbalance with the value of the VUF that go as high as 80%.

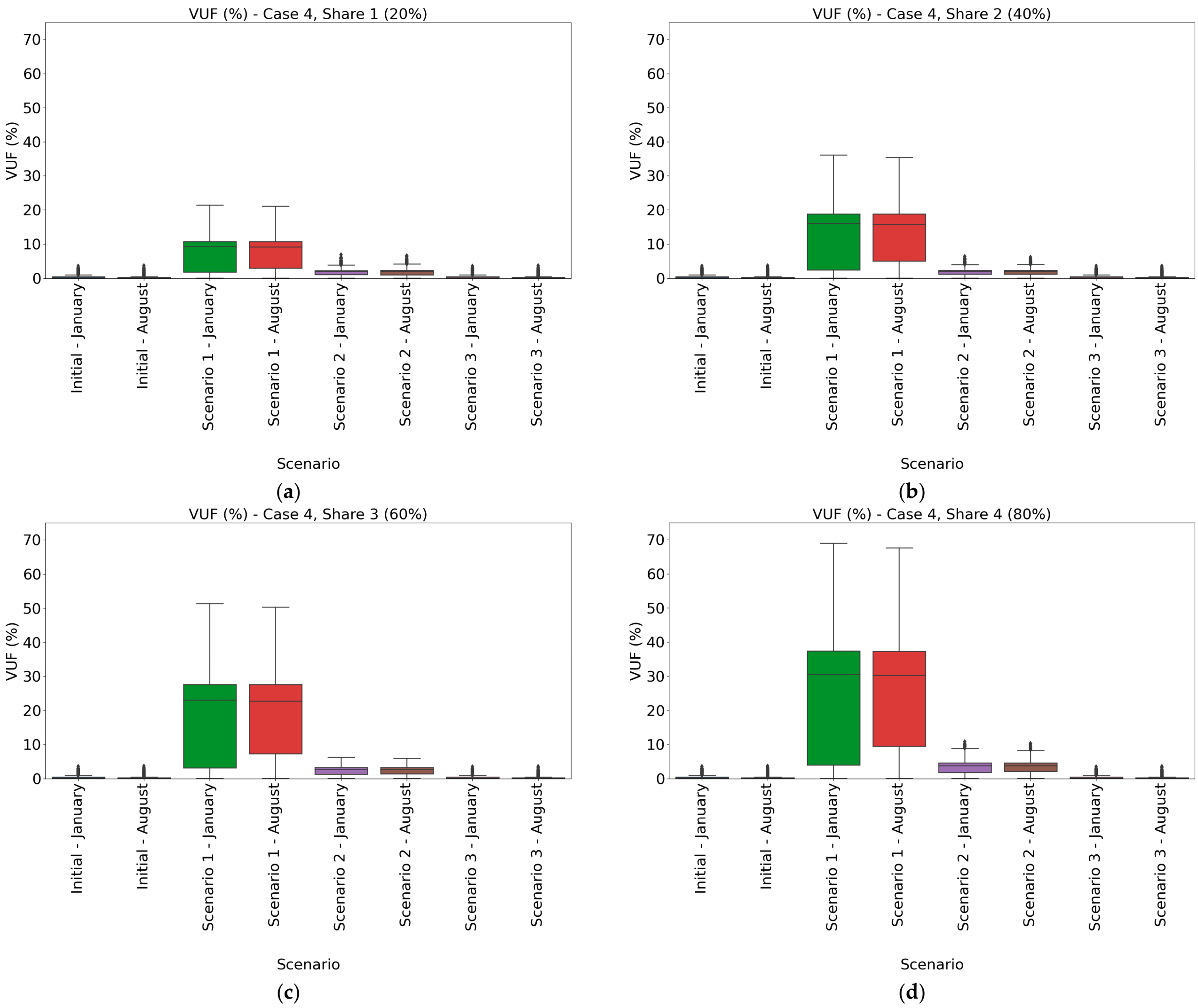

Figure 8. VUF (%)—Case 4; Share 1–Share 4; January, August.

However, it is important to emphasize the interquartile range in Case 4. The interquartile range is significantly higher than the one in the previous mentioned Case 2 and Case 3. That can be applied to all scenarios, shares and for both January and August. The other important thing is a smaller number of outlier values, which indicates that there is a small number of extreme situations in which the VUF values are outside the interquartile range. Therefore, from the DSO's perspective, a situation in which charging and discharging cycles of the battery storage are market driven, is not a preferred situation which should be encouraged in order to avoid or decrease the VUF values that are above set boundaries.

Comparing results of Case 4, depending the share and the month, shows that values of the VUF in Scenario 1 are more than twice larger compared to those in Scenario 2. Also, with the growth of the share of LC technologies, maximum values of the VUF in scenarios when LC technologies are connected to the same phase in each node grow faster. Maximum value for Share 1 is little less than 25% and for Share 4, maximum value passes 70%. When end-users connect LC technologies to a different phase at each node, VUF values do not exceed 10%.

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Figure 9a–d show that the previous mentioned occurrence of smaller values of the VUF does not necessarily mean that the situation in Case 4 is better than in other cases. Just the opposite, it is shown that Case 4 is the worst analyzed case in this paper. The analysis show that the most time in which the VUF is higher than the 2% limitations occurs in August, when in Scenario 1, Share 2–Share 4, VUF thresholds the limit in more than 80% of 10 min intervals during the observed week.

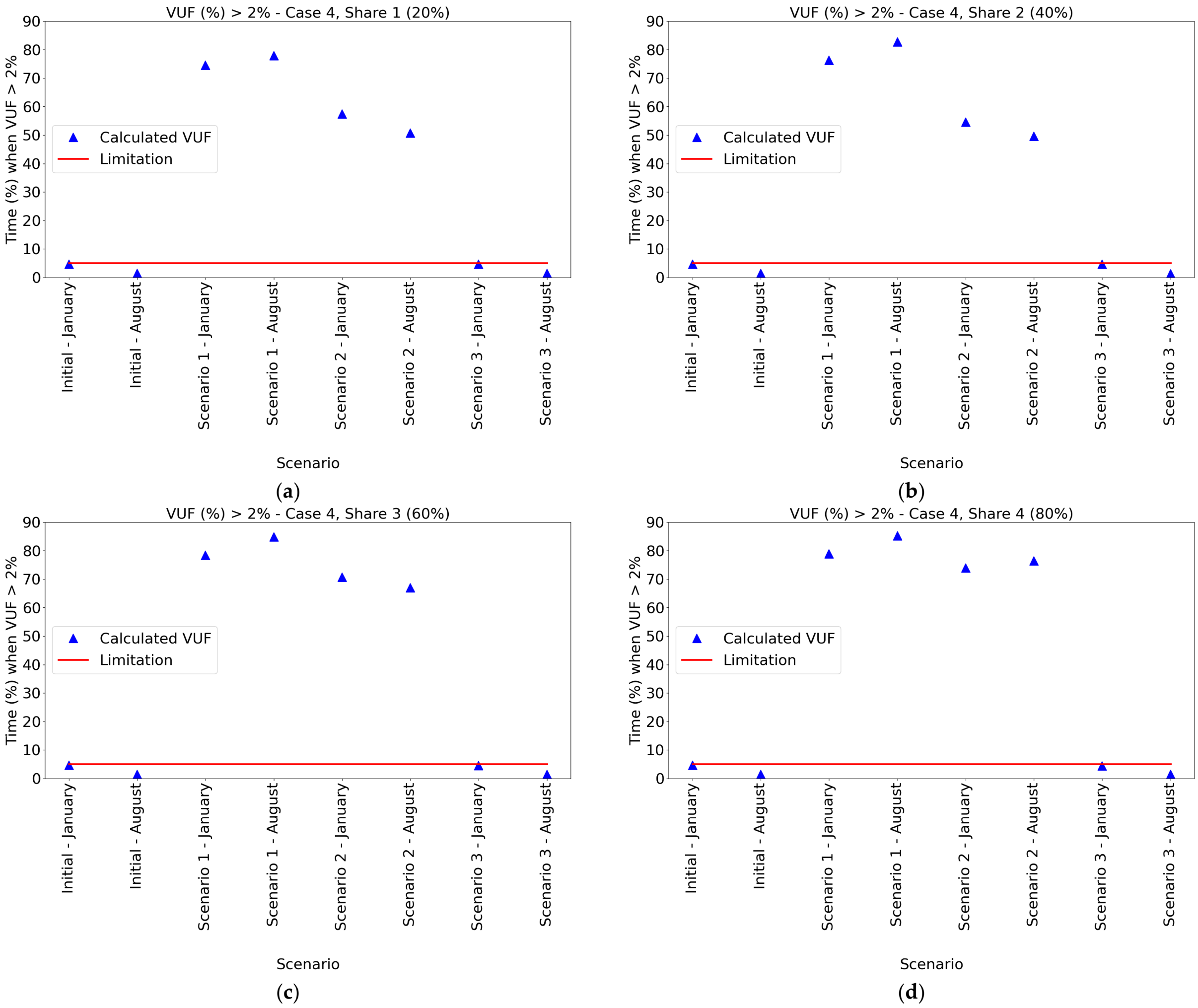

Figure 9. VUF > 2%—Case 4; Share 1–Share 4; January, August.

Same as in Case 3, the battery storage is used in Case 4. The difference is that in Case 3, battery storage is a modelled with the logic of the self-sufficiency. The comparison with Case 3 shows that changing the method which determines charging and discharging cycles does not significantly impact on the occasions related to the voltage unbalance, i.e., the occurrence of the VUF values thresholding the limit is almost as frequent as in Case 4 in Scenario 1. The difference in Scenario 2 is much more visible, which leads to the conclusion that changing the connection phase at each node improves the voltage unbalance. Results of Scenario 3 shows that a three-phase connection does not produce thresholding VUF values in alarming frequency.

Figure10presents the voltage magnitude results with the 80% of LC technologies connected, i.e., the worst-case scenario in terms of voltage limit violations. It can be noticed that in certain instances and scenarios the undervoltage occurs in time periods when the consumption is the highest, and there is no production from the PVs, while in certain instances and scenarios the overvoltage occurs in time periods when the consumption is lower, the PVs' production is high, and the battery storage is discharging. The lower voltage limitation is defined as 90% of the nominal voltage, and the upper limitation as 110% of the nominal voltage [27,49]. Since the DSO will definitely change it operational practices in case of large LC integration, either by reinforcing the network or by incorporating provision of flexibility services, further analyses on voltage magnitude are not in the focus of the paper.

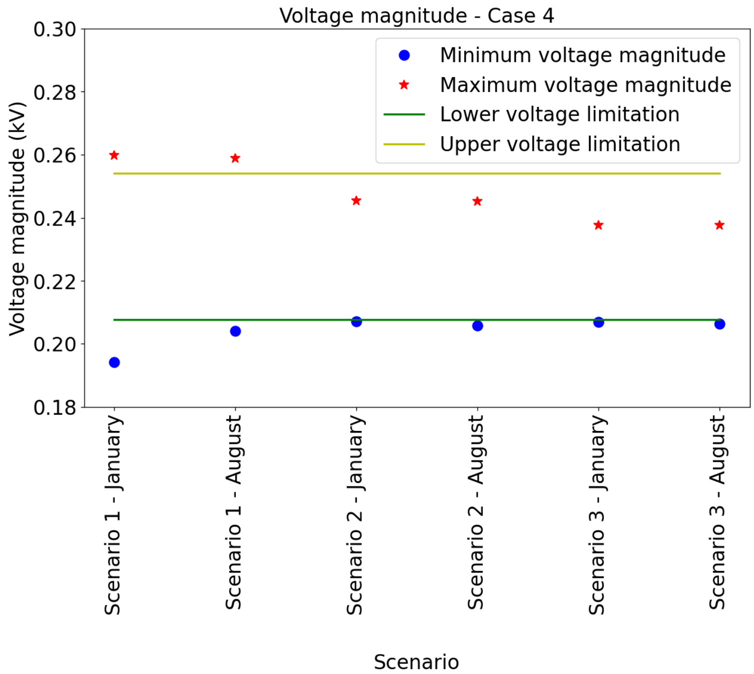

Figure 10. Minimum and maximum voltage magnitude—Case 4.

4. Conclusions

This paper provides a comprehensive and systematic analysis of the real distribution network PQ indicators related to the voltage unbalance, focusing on the impact of the different LC technologies, either alone or in joint operation, on these indicators. Different integration levels of PVs, residential battery storages and EV charging stations are modelled and their impact is evaluated over a set of operational regimes. The results are shown for a representative part of the real-world distribution network in Croatia and put in the context of boundary values for the VUF set by standards and grid codes.

Four different cases are selected in order to assess the impact of LC technologies on the absolute value of the VUF as well as on the time periods when the VUF is larger than the set limit defined by General Summation Law described in IEC 61000-3-13. Case 1 includes only PVs, while in Case 2 the end-users have an additional option of the EV charging. Further, in Case 3 a battery storage is added to the above, coordinating the operation of all devices with the goal of maximizing self-sufficiency. Finally, in Case 4 all mentioned LC technologies are operated driven by DA market prices aiming at reducing total end-user's operational costs.

All of the above-described cases are run over a set of scenarios, each presenting different connection to the distribution network. In Scenario 1 all LC technologies are connected to the same phase at each node. Even though it is highly unlikely that all end-users are connected to the same phase, it presents the worst-case scenario when almost all observed parameters are worse than in other scenarios. In Scenario 2, LC technologies are connected to different phases in different nodes, where the selected connection phase is the result of a developed random phase generator model. Scenario 3 presents the scenario in which LC technologies are three-phase connected, i.e., the value of production/consumption is symmetrically distributed to all three-phases.

Even though it is expected that no matter the case, single-phase connected LC technologies have negative impact on the voltage unbalance, different analyses presented in the paper show that even when only 20% of end-users install single-phase connected PVs, the value of the VUF is thresholding the 2% limitation set in [27,28] in almost 20% of the time. by almost 20% of the time. As the percentage of installed PVs grows (but also that of other technologies such as batteries and EVs), the value of VUF and the frequency of VUF overstepping the limitations is further increasing. As there is a direct link between these values and increased network losses [37], the system operator needs to ensure that the operational practice adopt to the new situation in order not to unnecessary increase the networks operational costs. In some cases, when the share of LC technologies is 80%, the value of VUF presents serious issues and challenges for the DSO. The worst case is Case 2 when the value of VUF exceeds 80% in Scenario 1, both in January and August.

Additionally, the paper analyses duration of the VUF being higher than 2% as defined per IEC 61000-3-13. Results are in line with those in the first analysis, problems occur in all cases, i.e., VUF is higher than 2% in more than 5% of 10 min intervals. The worst case is Case 4 (market drive operation), when the unallowed VUF occurs in around 85% of observed 10 min intervals in the worst-case scenario (Scenario 1). The scenario in which the values do not exceed boundaries more than it is set in the standard is Scenario 3, when LC technologies are three-phase connected.

Results show that in order to avoid problems related to the voltage unbalance, end-users should be encouraged to three-phase connect their LC technologies. Even though changing the phase of connection at each node is better solution than connecting LC technologies to the same phase at each node, results of Scenario 1 show that there is a high possibility of an occurrence of problems related to the voltage unbalance, even when end-users do not connect LC technologies to the same phase. A three-phase connection of LC technologies does not only reduce the value of the VUF and the frequency of the occurrence of the VUF thresholding the limit, but also enables higher power injection into the network. The available literature proposed a number of operational actions that can be suggested in order to reduce the network voltage unbalances, however majority of them requires complex models and control algorithms on the side of both end-users and the distribution system operator. Since, according to the Croatian Grid Code [49], end-users that are connecting to the network with the production power higher than 3.68 kW are already obligated to ensure three-phase connection to the network, recommending having all new LC devices connected as balanced three-phase ones, is the most simplistic solution and the most realistic one to be implemented in the near future. The results in the paper support such a recommendation and are, to the authors knowledge, the first time such benefits are quantified on realistic models and networks.

Even though results show the concerning trend from the perspective of the DSO, they could be observed as the worst-case scenario. The voltage unbalance has an impact on the performance of the end-user's equipment, mostly on asynchronous machines and the number of asynchronous machines in the LV network is not so large. However, with the process of the electrification of the heating, there will be growth in a number of heat pumps, which are basically asynchronous machines. With trend shown in this paper, the performance of heat pumps will be reduced, and losses will be significantly higher. Therefore, DSOs should be looking for solutions that can mitigate the voltage unbalance in the network and simultaneously enable higher penetration of LC technologies in the LV network.

Since the voltage unbalance is directly connected to the performance of the equipment and network losses, it causes significant financial losses. The authors in [37] showed that there is direct connection between voltage unbalance and network losses. In case of a 15% unbalance, the network losses increase by 15%. Since the annual financial value of 1% network losses in Croatia is around 6,000,000 €, the system operator would like to reduce network losses and not increase them. The method proposed in this paper enables system operators to reduce costs without complex operations and investment in the equipment.

Even though end-user's devices are single-phase, a lot of end-users in the Croatian LV distribution network are three-phase, meaning that they have access to all three-phases. In that case, the additional costs could be related to connection fees to the DSO or potential higher equipment investment for the end-user.

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Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

	Indices
n	Index that determines observed node, $n \in N$
t	Index that determines observed time period, $t \in T$
	Variables
$P_{n,t}^{ch,bat}$	Charging power of the battery at every node and every time period
$P_{n,t}^{dis,bat}$	Discharging power of the battery at every node and every time period
$P_{t}^{ch,EV}$	Charging power of the battery in the EV in every time period
$SOC_{n,t}^{bat}$	State of charge of the battery at every node and every time period
$P_{n,t}^{delta}$	Difference between consumption and production at every node and every time period
$P_{n,t}^{delta,pos}$	Positive difference between consumption and production at every node and every time period
$P_{n,t}^{delta,neg}$	Negative difference between consumption and production at every node and every time period
	Binary variables
$x_{n,t}^{ch,bat}$	Binary variable that determines if the battery is charging at the observed node and in the observed time period
$x_{n,t}^{dis,bat}$	Binary variable that determines if the battery is discharging at the observed node and in the observed time period

Parameters

$p^{ch,bat\ max}$	Maximum charging power of the battery, 1.8 kW for VARTA and 5 kW for Tesla Powerwall battery
$p^{dis,bat\ max}$	Maximum discharging power of the battery, 1.6 kW for VARTA and 5 kW for Tesla Powerwall battery
$p^{ch,EV\ max}$	Maximum charging power of the battery in the EV, 3.6 kW for Nissan Leaf
$p^{ch,EV\ min}$	Minimum charging power of the battery in the EV, 0 kW
SOC^{bat}_{max}	Maximum state of charge of the battery, 3.3 kWh for VARTA and 13.5 kWh for Tesla Powerwall battery
$SOC^{EV\ max}$	Maximum state of charge of the battery in the EV, 36 kWh for Nissan Leaf
$SOC^{EV\ min}$	Minimum state of charge of the battery in the EV defined by the end-user
$P^{PV}_{n,t}$	Power of the PV production at every node and every time period
$P^{load}_{n,t}$	Power of the load at every node and every time period
p^{DA}_{t}	Price of electricity on day-ahead market in the observed time-period
τ	Constant that is equal to 10 min

Appendix A

Figures A1 and A2 show the load profile curve for each phase in January and August. The load profile curve was used to determine the value of the consumption of each end-user in every time period.

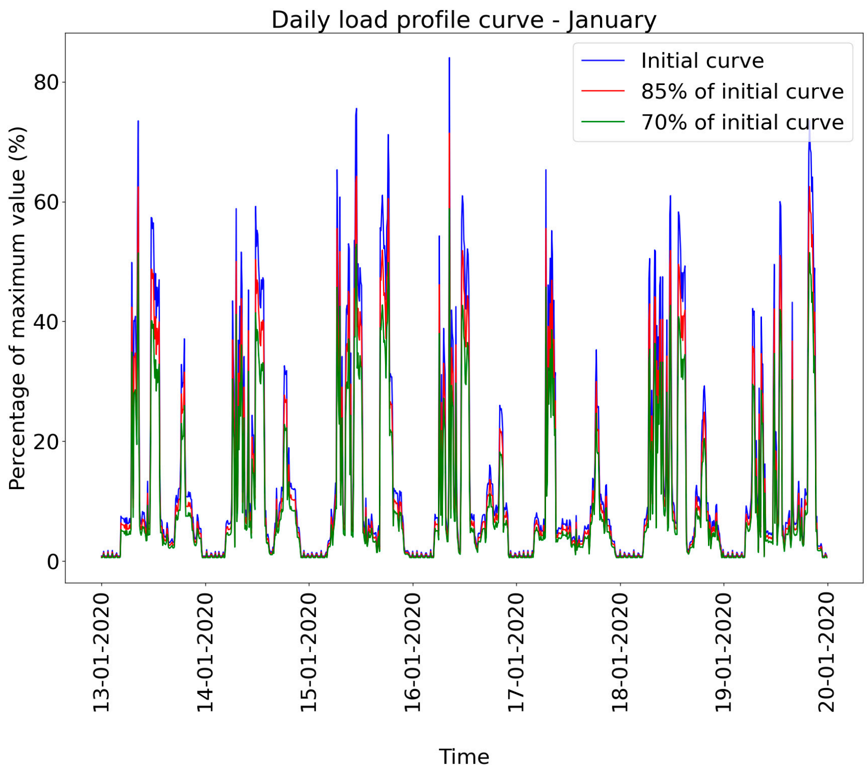

Figure A1. Load profile curve–January.

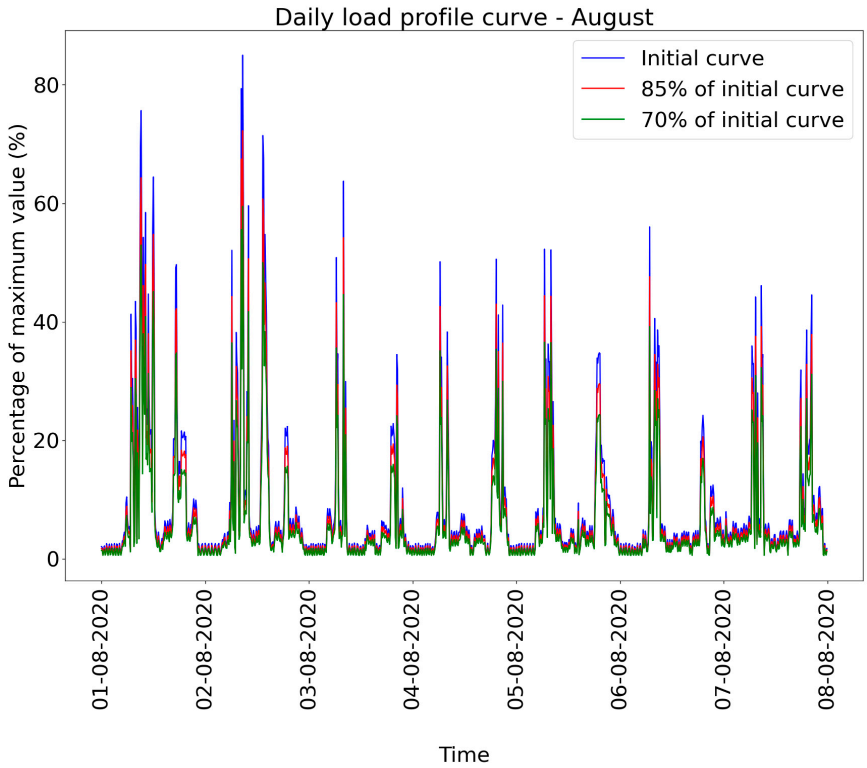

Figure A2. Load profile curve—August.

Figures A3 and A4 represent the PV production profile curve on the ten-minute basis for every day in the week in January and August. The PV production power of the end-user with the installed PV was calculated from the daily PV production profile curve.

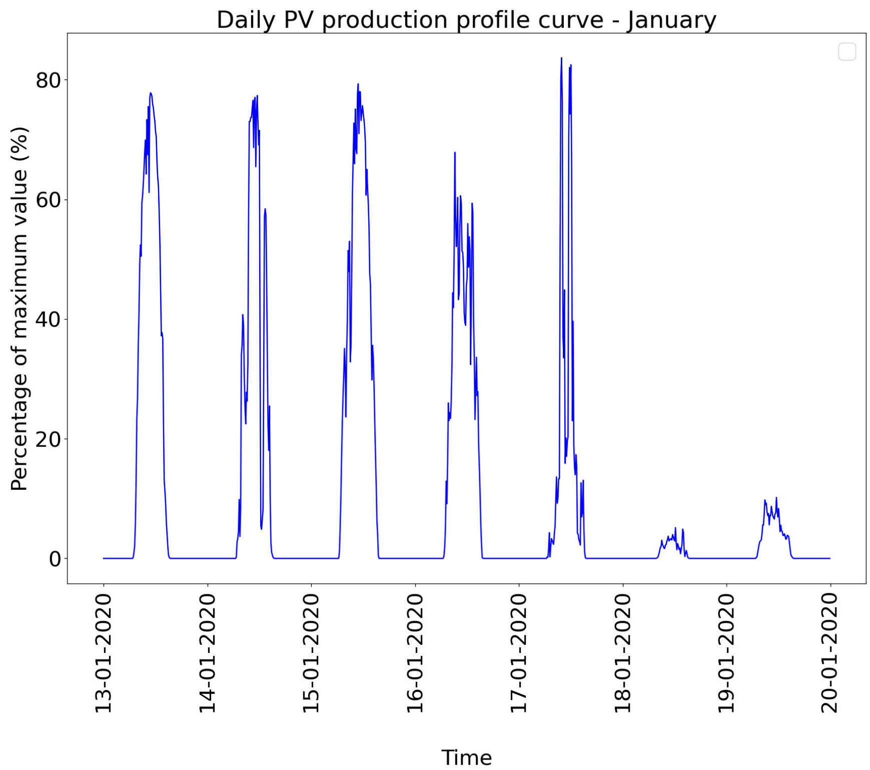

Figure A3. PV production profile curve—January.

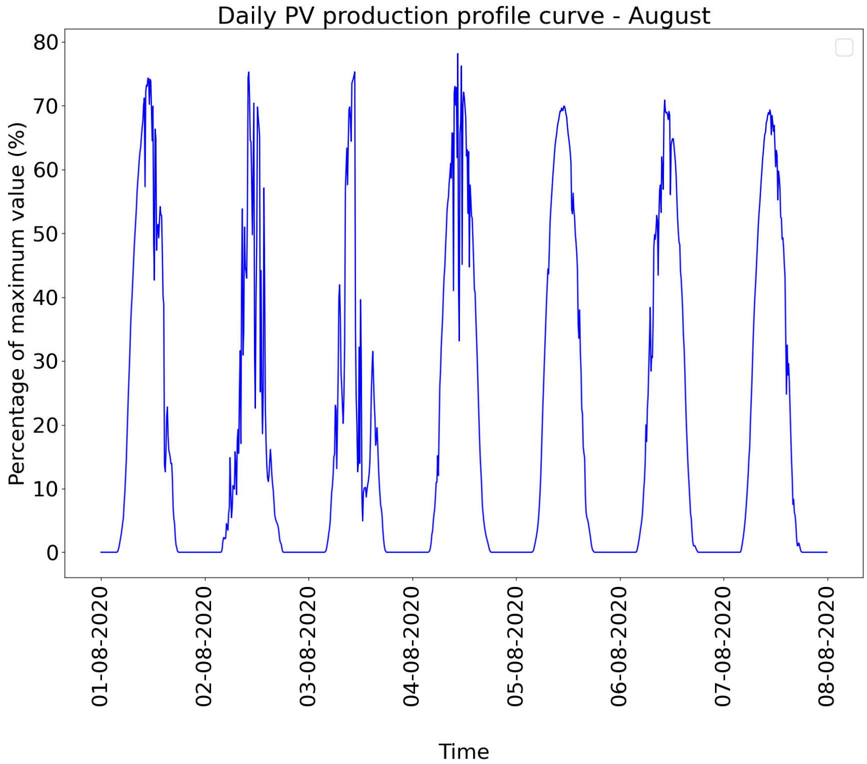

Figure A4. PV production profile curve—August.

Figures A5 and A6 show the charging and the discharging power of the battery storage in the node LV100, when the battery is modelled with the logic of self-sufficiency (Method 1).

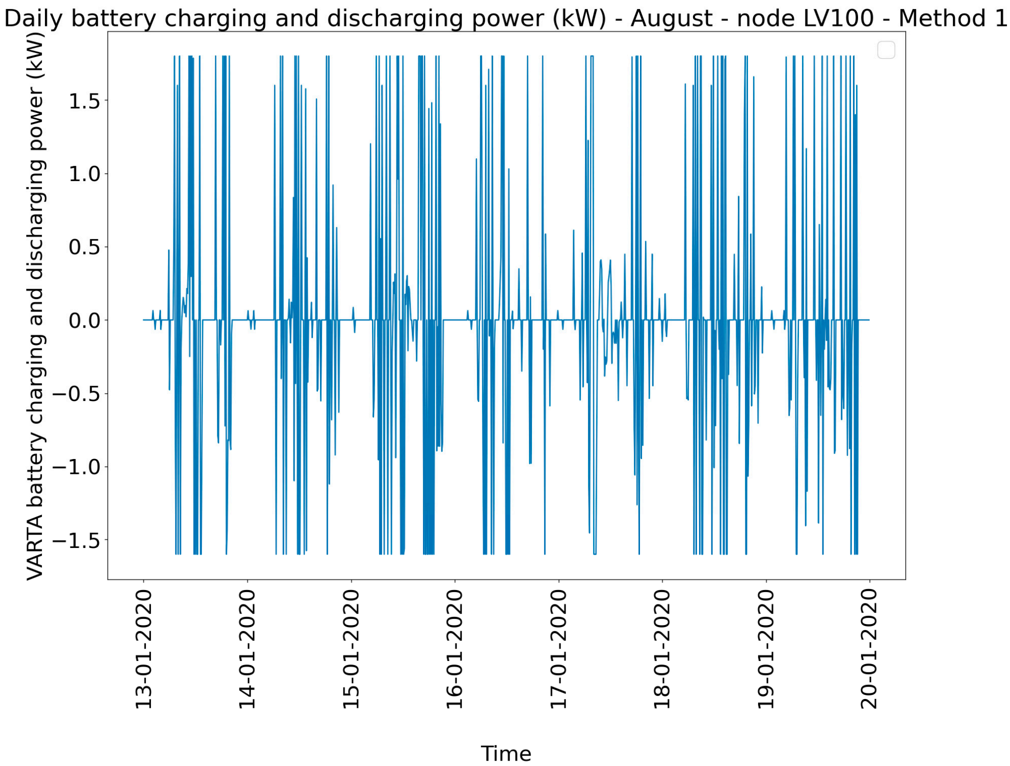

Figure A5. VARTA battery charging and discharging curve—January—Method 1.

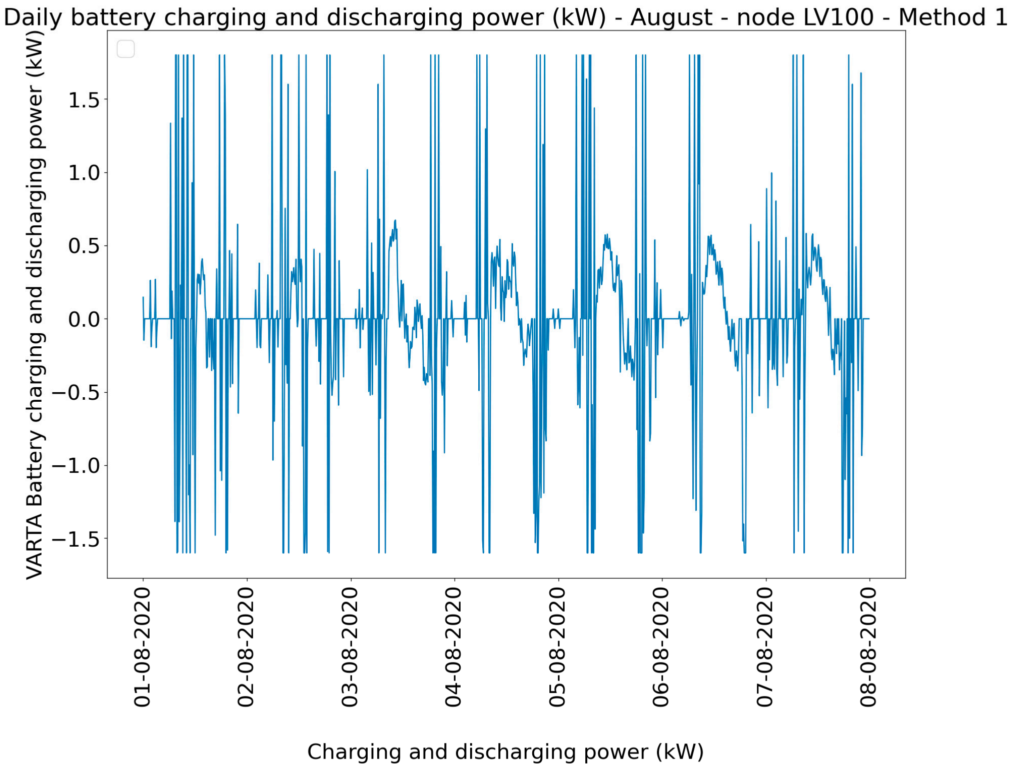

Figure A6. VARTA battery charging and discharging curve—August—Method 1.

Figures A7 and A8 show the charging and the discharging power of the battery storage in the node LV100, when the battery is modelled as the end-users are active DA market participants (Method 2).

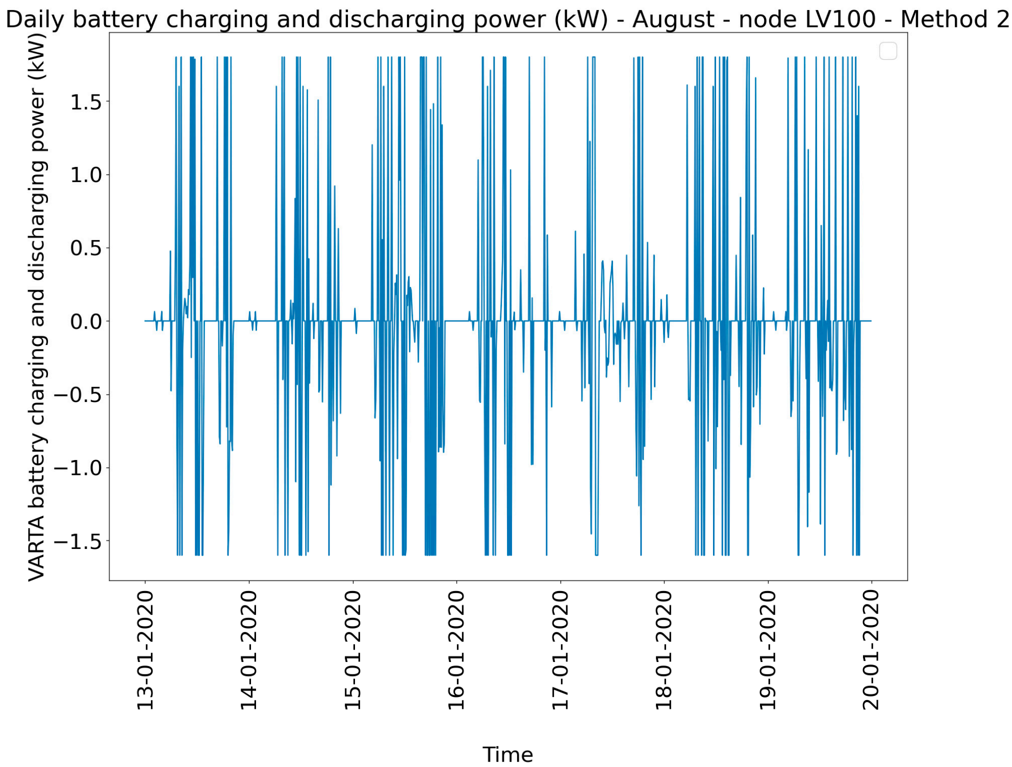

Figure A7. VARTA battery charging and discharging curve—January—Method 2.

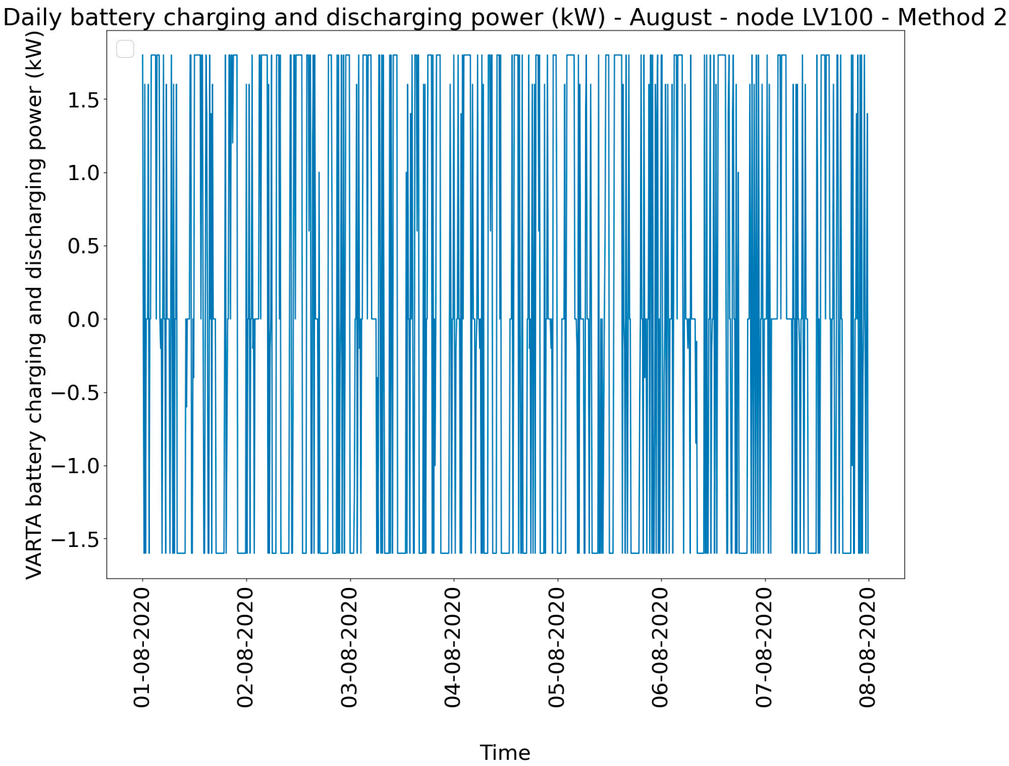

Figure A8. VARTA battery charging and discharging curve—August—Method 2.

Table A1. EV charging power in January.

Time	EV Charging Power (kW)						
	13-01-20	14-01-20	15-01-20	16-01-20	17-01-20	18-01-20	19-01-20
0:00–0:10	3.6	0	0	3.6	0	0	0
0:10–0:20	3.6	0	0	3.6	0	0	0.72
0:20–0:50	3.6	0	0	3.6	0	0	0
1:00–1:50	3.6	0	0	3.6	0	0	3.6
2:00–2:10	3.6	0	3.6	3.6	3.6	3.6	3.6
2:10–2:20	3.6	0	3.6	3.6	0	3.6	3.6
2:20–2:30	3.6	0	3.6	3.6	3.6	3.6	3.6
2:30–2:40	3.6	0	3.6	3.6	0	3.6	3.6
2:40–2:50	3.6	0	0.48	3.6	1.2	1.92	3.6
2:50–3:00	3.6	0	3.6	3.6	0	0	3.6
3:00–3:30	3.6	0	3.6	3.6	3.6	3.6	3.6
3:30–3:40	3.6	3.6	3.6	3.6	3.6	3.6	3.6
3:40–3:50	3.6	1.68	3.6	3.6	3.6	3.6	3.6
3:50–4:00	3.6	3.6	3.6	3.6	3.6	3.6	3.6
4:00–4:20	3.6	0	3.6	3.6	3.6	3.6	3.6
4:20–4:30	3.6	3.6	3.6	3.6	3.6	3.6	3.6
4:30–4:40	3.6	0	3.6	3.6	3.6	3.6	3.6
4:40–5:00	3.6	3.6	3.6	3.6	3.6	3.6	3.6
5:00–5:20	0	0	0	0	0	0	0
5:20–5:30	0	0	0	1.68	0	0	0
5:30–5:40	0	0	0	3.6	0	0	0
23:00–23:50	0	0	0	3.6	0	0	3.6

Table A2. EV charging power in August.

Time	EV Charging Power (kW)						
	01-08-20	02-08-20	03-08-20	04-08-20	05-08-20	06-08-20	07-08-20
0:00–0:10	0	0	0	3.6	0	0	3.6
0:10–0:30	0	0	0	3.6	0	0	0
0:30–0:40	0	0	0	3.6	0	0	0.72
0:40–1:00	0	0	0	3.6	0	0	0
1:00–2:00	3.6	0	0	3.6	0	0	3.6
2:00–2:40	3.6	0	3.6	3.6	0	3.6	3.6
2:40–2:50	3.6	0	0.48	3.6	0	3.6	3.6
2:50–3:00	3.6	0	3.6	3.6	0	3.6	3.6
3:00–4:00	3.6	0	3.6	3.6	3.6	3.6	3.6
4:00–4:10	3.6	1.68	3.6	3.6	3.6	3.6	3.6
4:10–4:30	3.6	0	3.6	3.6	3.6	3.6	3.6
4:30–4:40	3.6	0	3.6	3.6	3.6	0	3.6
4:40–4:50	3.6	0	3.6	3.6	3.6	3.6	3.6
4:50–5:00	3.6	0	3.6	3.6	3.6	1.32	3.6
5:00–5:10	3.6	3.6	0	3.6	0	0	3.6
5:10–5:30	3.6	3.6	0	3.6	3.6	0	3.6
5:30–5:40	3.6	3.6	0	3.6	1.2	0	3.6
5:40–5:50	3.6	3.6	0	3.6	0	0	3.6
23:00–23:10	3.6	0	0	1.68	0	0	0
23:10–23:30	0	0	0	3.6	0	0	0

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Solving scalability issues in calculating PV hosting capacity in low voltage distribution networks

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***Abstract*—The share of end-users with installed rooftop photovoltaic (PV) systems is continuously growing. Since most end-users are located at the low voltage (LV) level and due to technical limitations of LV networks, it is necessary to calculate PV hosting capacity. Most approaches in calculating a network's hosting capacity are based on three-phase optimal power flow (OPF) formulations. Linearized and relaxed three-phase OPF formulations respectively lose their accuracy and exactness when applied to solve the hosting capacity problem, and only non-linear programming (NLP) models guarantee the exact solution. Compared to linearized or relaxed models, NLP models require a higher computational time for finding an optimal solution. The binary variables uplift the problem to mixed-integer (MI)NLP and increase the computational burden. To resolve the scalability issues in calculating the hosting capacity of single-phase connected PVs, we propose a method that does not entail binary variables but still ensures that PVs are not connected to more than one phase at a time. Due to a risk of a sub-optimal solution, the proposed approach is compared to the results obtained by the MINLP formulation. The comparison includes values of the solution time and technical quantities such as network losses, voltage deviations, and voltage unbalance factor.**

***Index Terms*—hosting capacity, low voltage networks, scalability, three-phase optimal power flow**

I. Introduction

A. Motivation and Literature Review

Installation of photovoltaic (PV) units in low voltage (LV) distribution networks ensures consumption of locally generated electricity and helps decrease end-users electricity costs [1]. At the same time, the installation of PVs is often uncoordinated, negatively affecting technical conditions and complicating the planning and operation of distribution networks [2]. It is necessary to determine the maximum power of PVs that can be installed in a network to prevent uncoordinated integration, i.e., PV hosting capacity that will ensure the increase in the share of PVs without violating any network's technical constraints [3].

Most of the methods for calculating PV hosting capacity are based on the power flow simulations but other approaches can also successfully resolve the given problem [4], [5]. When observing LV networks, power flow formulations become much more complex due to the network structure, mutual effects of phases, relatively high R/X ratio, and additional constraints such as voltage unbalance. Therefore, iterative approaches such as the one presented by Joshi and Gokaraju [6] may take time to find the solution. Due to numerous uncertainties in LV distribution networks, deterministic methods, as one described by Hashemi et al. [7] are being replaced by stochastic approaches [8]. Stochasticity and uncertanties in an LV network further increase the complexity of a given problem. Some papers put forward scenario reduction techniques to mitigate the problem [9]. There is a lack of PV hosting capacity methods that are based on non-linear (NLP) optimal power flow (OPF) models, mostly due to the complexity of the formulation and the larger computational time needed to find the optimal solution. Therefore, other formulations, including approximation or linearization, are used for solving OPF problems [10]. Despite the benefits of using other formulations, NLP models are the only ones that ensure the exact solution without any loss of accuracy. Linearized formulations lose accuracy when the operating point varies by a great deal and hence, do not suit the intended application. For relaxed formulations to work, some conditions should hold. Specifically, the objective function of the hosting capacity problem poses challenges to the application of relaxed formulations. In an unbalanced system, the mutual effects of phases, upper bound voltage limits (which is specifically important in the hosting capacity problem), the limit on unbalance factor, and modelling the discrete control devices, e.g., voltage regulators, may put the relaxation far from being exact. To bridge the identified gap, hosting capacity in this paper is evaluated using an exact NLP formulation of the OPF model.

Another identified gap in the papers that observe a single-phase connection of PVs is the lack of constraints that ensure such a connection. The methodology proposed by Ceylan et al. [11] is based on randomization and an iterative process that does not guarantee an optimal phase selection and optimal solution. A single-phase connection of PVs is also observed by Mulenga et al. [8], and uncertainties related to parameters, including the connection phase, are modelled using a stochas-

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tic approach. We propose an approach that introduces binary variables to determine the optimal connection phase. However, this uplifts the problem to mixed integer (MI)NLP, increasing complexity of the problem. Therefore, four other formulations that are based on randomization and predetermining the connection phase and do not include binary variables are presented in our work. Solutions obtained by different approaches for the same case study are found, and the proposed approach is validated by comparing various variables and quantities between the solution of the proposed approach and an exact MINLP approach.

B. Contributions

To summarize, the main contributions of the paper are:

- We use an exact NLP formulation of the three-phase OPF model in calculating single-phase PV hosting capacity.
- The problem is uplifted to the MINLP formulation in order to ensure the accurate solution that is to be used as the benchmark.
- Finally, selection of the optimal connection phase using binary variables is replaced with randomization process. The solution is compared to the one found using the accurate MINLP formulation in terms of the computational time and accuracy.

The rest of the paper is organized as follows: the OPF mathematical model and methodology for determining a PV system connection phase is presented in Section II, case studies are described in Section III, results are shown in Section IV, and final conclusions are given in Section V.

II. Methodology

The problem of calculating the PV hosting capacity is modelled with a non-convex, non-linear three-phase OPF formulation, implemented in the tool presented in [12]. The OPF formulation used for calculating the hosting capacity of single-phase connected PVs is modelled as the current-voltage formulation.

A. Optimal Power Flow Model

Real and imaginary part of voltage drop of all phases p for a branch l connecting nodes i and j is calculated using (1) and (2):

$$U^{re}_{j,p,t} = U^{re}_{i,p,t} - \sum_{q\in\{a,b,c\}} R_{l,pq} \cdot I^{re}_{l,ij,q,t} + \sum_{q\in\{a,b,c\}} X_{l,pq} \cdot I^{im}_{l,ij,q,t} \tag{1}$$

$$U^{im}_{j,p,t} = U^{im}_{i,p,t} - \sum_{q\in\{a,b,c\}} R_{l,pq} \cdot I^{im}_{l,ij,q,t} - \sum_{q\in\{a,b,c\}} X_{l,pq} \cdot I^{re}_{l,ij,q,t} \tag{2}$$

Active and reactive power flow in branch l, connecting nodes i to j are constrained with (3) and (4).

$$P_{l,ij,p,t} = U^{re}_{i,p,t} \cdot I^{re}_{l,ij,p,t} + U^{im}_{i,p,t} \cdot I^{im}_{l,ij,p,t} \tag{3}$$

$$Q_{l,ij,p,t} = U^{im}_{i,p,t} \cdot I^{re}_{l,ij,p,t} - U^{re}_{i,p,t} \cdot I^{im}_{l,ij,p,t} \tag{4}$$

Real and imaginary part of currents of loads and PVs are calculated with (5) and (6). These expressions are valid for all nodes n in an LV network.

$$P^{load/PV}_{n,p,t} = U_n, p, t^{re} \cdot (I^{load/PV}_{n,p,t})^{re} + U^{im}_{n,p,t} \cdot (I^{load/PV}_{n,p,t})^{im} \tag{5}$$

$$Q^{load/PV}_{n,p,t} = U^{im}_{n,p,t} \cdot (I^{load/PV}_{n,p,t})^{re} - U^{re}_{n,p,t} \cdot (I^{load/PV}_{n,p,t})^{im} \tag{6}$$

Kirchoff's Current Law (KCL) for both real and imaginary part is ensured implementing (7).

$$(I^{load}_{i,p,t})^{re/im} - (I^{PV}_{i,p,t})^{re/im} - I^{re/im}_{l,h\rightarrow i,p,t} + I^{re/im}_{l,i\rightarrow j,p,t} = 0 \tag{7}$$

In calculating an LV network's PV hosting capacity, it is important to define a set of technical constraints that will limit the generation of a PV system accordingly to values of phase voltage magnitudes, currents that flow through a transformer and LV lines, and voltage unbalance factor (VUF) in every node. Therefore, (8)-(12) are introduced. The maximum value of each line's current is defined as the input parameter and it changes depending on the type of a line or transformer. The minimum value of voltage magnitude is 0.9 p.u. and the maximum value is equal to 1.1 p.u. Based on definitions in the EN 50160 standard [13] and the Croatian distribution grid code [14], VUF cannot be larger than 2%.

$$(I^{re}_{l,ij,p,t})^2 + (I^{im}_{l,ij,p,t})^2 \leq (I^{max}_{l,ij})^2 \tag{8}$$

$$(U^{min})^2 \leq (U^{re}_{n,p,t})^2 + (U^{im}_{n,p,t})^2 \leq (U^{max})^2 \tag{9}$$

$$\frac{|U_{n,2,t}|^2}{|U_{n,1,t}|^2} \leq (VUF^{max}_n)^2 \tag{10}$$

$$\begin{aligned} |U_{n,2,t}|^2 = {} & [U^{re}_{n,a,t} - \frac{1}{2} \cdot (U^{re}_{n,b,t} + U^{re}_{n,c,t}) + \\ & \frac{\sqrt{3}}{2} \cdot (U^{im}_{n,b,t} - U^{im}_{n,c,t})]^2 + [U^{im}_{n,a,t} - \\ & \frac{1}{2} \cdot (U^{im}_{n,b,t} + U^{im}_{n,c,t}) - \frac{\sqrt{3}}{2} \cdot (U^{re}_{n,b,t} - U^{re}_{n,c,t})]^2 \end{aligned} \tag{11}$$

$$\begin{aligned} |U_{n,1,t}|^2 = {} & [U^{re}_{n,a,t} - \frac{1}{2} \cdot (U^{re}_{n,b,t} + U^{re}_{n,c,t}) - \\ & \frac{\sqrt{3}}{2} \cdot (U^{im}_{n,b,t} - U^{im}_{n,c,t})]^2 + [U^{im}_{n,a,t} - \\ & \frac{1}{2} \cdot (U^{im}_{n,b,t} + U^{im}_{n,c,t}) + \frac{\sqrt{3}}{2} \cdot (U^{re}_{n,b,t} - U^{re}_{n,c,t})]^2 \end{aligned} \tag{12}$$

B. Determining a PV System Connection Phase

PVs installed in LV networks can be single-phase or three-phase connected. Even though the single-phase connection is limited with relatively lower power, the implementation of such a connection is cheaper and simpler than a three-phase connection. The physical solution for ensuring a single-phase connection is easy to understand, however integration of the constraint in the mathematical model is not as intuitive and requires the introduction of binary variables. A single-phase connection of a PV system is implemented with (13)-(14).

$$P^{PV}_{n,p,t} \leq x^{PV}_{n,p,t} \cdot (P^{PV})^{max} \cdot PV^{curve}_{t} \quad (13)$$

$$\sum_{p\in\{a,b,c\}} x^{PV}_{n,p,t} \leq 1 \quad (14)$$

The maximum power $(P^{PV})^{max}$ of a single-phase connected PV system is equal to $3.68kW$, as defined in the national distribution grid code [14]. However, the defined limit is a static one, meaning that its value remains the same, without considering network conditions such as network topology or demand. Moreover, the single-phase connection limit is relatively low, and larger deviations in terms of the value of the objective function are not expected. Therefore, we define a second scenario in which the maximum power $(P^{PV})^{max}$ is equal to $100kW$, which is the maximum value of PV systems that can be connected to a Croatian LV network. Such an approach is also in line with the recent trend of abandoning static export limits and the use of dynamic operating envelopes instead [15]. Additionally, PV^{curve}_{t} is the parameter created based on the irradiance and it further limits the PV generation but also ensures that there is no generation during the night or cloudy hours and that it is not possible to have maximum generation at all time periods.

Since the introduction of binary variables in the model uplifts the model from NLP to MINLP, the complexity of the model and an increase in the computational time are expected. To resolve the problem but still keep the NLP formulation, we propose four different approaches.

In the first and the second approach, a PV system is connected to a randomly selected phase as shown with (15)-(17). The difference is that in one solution, the phase connection is randomly selected in every time period of the optimization process, and in the other, the connection phase is selected only once before the start of the optimization process and it remains the same in all time periods.

$$q = random\{a,b,c\} \quad (15)$$

$$P^{PV}_{n,p=q,t} \leq (P^{PV})^{max} \cdot PV^{curve}_{t} \quad (16)$$

$$P^{PV}_{n,p\neq q,t} = 0 \quad (17)$$

In the third approach, it is also assumed that the connection phase can change at every time period. However, unlike in previous solutions, the connection phase in this one is the same as the most loaded one, in order to maximally balance the total demand in every node. The final approach is similar to the previous one, with the exception of having the fixed PV system connection phase. In this approach, D is determined as the maximum of sum of phase demand values over time. Eq. (18) presents determining the highest demand D in the last two approaches. The method for determining the PV system connection phase q is shown with Algorithm 1. Constraining the maximum PV system generation power and ensuring single-phase connection is represented with (16) and (17).

$$\begin{aligned} D &= \max\{P^{load}_{n,p=a,t}, P^{load}_{n,p=b,t}, P^{load}_{n,p=c,t}\} \\ D &= \max\{\sum_{t\in T} P^{load}_{n,p=a,t}, \sum_{t\in T} P^{load}_{n,p=b,t}, \sum_{t\in T} P^{load}_{n,p=c,t}\} \end{aligned} \quad (18)$$

Algorithm 1 Determining a PV system's variable connection phase

if $D = P^{load}_{n,p=a,t}$ *or* $D = \sum_{t\in T} P^{load}_{n,p=a,t}$ **then**
  $q = a$
else if $D = P^{load}_{n,p=b,t}$ *or* $D = \sum_{t\in T} P^{load}_{n,p=b,t}$ **then**
  $q = b$
else if $D = P^{load}_{n,p=c,t}$ *or* $D = \sum_{t\in T} P^{load}_{n,p=c,t}$ **then**
  $q = c$
end if

Following the mathematical formulation of four different approaches, each of them is defined as an input in the presented OPF formulation used in the calculation of an LV network PV hosting capacity.

C. Objective Function

As previously stated, the aim of calculating the PV hosting capacity is to determine the maximum production of PVs, without violating any technical constraints in a distribution network. Therefore, the objective function is given in (19).

$$\max \sum_{n\in N_{PV}} \sum_{p\in a,b,c} \sum_{t\in T} P^{PV}_{n,p,t} \cdot \frac{1}{4}h \quad (19)$$

Since demand measurements are collected in 15-minute intervals, the generation power of PV systems is calculated in the same time interval. Therefore, it is necessary to convert generation power $P^{PV}_{n,p,t}$ to energy using factor $\frac{1}{4}$, which is equal to 15 minutes.

Even though the hosting capacity is defined as the maximum amount of PVs or other technology that can be installed in a network without violating any technical constraints and endangering the safe and reliable operation of a network, we focused on maximizing the PV generation instead of installed power. Even though the objective functions of calculating PV hosting capacity and maximum PV generation are similar in their formulation, PV hosting capacity will not change as much as maximum generation due to the low PV power limit. Therefore, the objective function is as defined above.

Besides the values of the objective function in different case studies, we compare the computational time needed for solving the optimization problem, total active network losses, voltage magnitude, and VUF values.

III. Case Study

The loss of accuracy caused by removing binary variables from the formulation used in calculating PV hosting capacity is tested on a mathematical model of a real-world residential LV feeder shown in Fig. 1. The feeder consists of one MV bus, 63 LV nodes, 62 underground cables, MV/LV transformer, and 64 unbalanced loads. Phase consumption curves for each end-user are created using measurements collected from smart meters installed in a feeder.

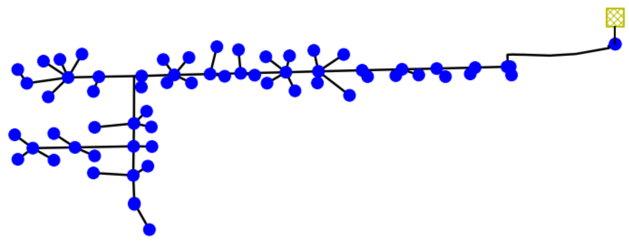

Fig. 1. A residential LV feeder

For the purpose of analyzing the impact of the PV hosting capacity formulation on the potential loss of accuracy, we define following case studies:

- CS 1: MINLP formulation is used for determining the optimal connection phase of a PV system
- CS 2: connection phase of a PV system is randomly assigned in every time period
- CS 3: connection phase of a PV system is randomly assigned but is the same in every time period
- CS 4: connection phase changes in each time period and it is equal to the most loaded phase
- CS 5: connection phase is the same in all time periods and it is equal with the highest summed value of active power

A formulation used in CS 1 is the only one ensuring the optimal solution of the hosting capacity calculation. However, as mentioned before, the use of binary variables is expected to make the problem even more complex. In order to tackle the complexity of the PV hosting capacity calculation, we introduce CS 2 - CS 5. Phase switching devices are utilized for balancing the network and removing unbalance problems in a network. Therefore, under the assumption that they are already installed, it is possible to consider the impact of the change of connection phase on the value of objective function and other investigated quantities, as presented in CS 1. The same assumption is introduced in CS 2 in which the use of binary variables is replaced by random selection of connection phase in every time period. That way, the OPF formulation remains nonlinear but the single-phase connection and the change of the connection phase remain ensured, which allows the comparison of the value of the objective function and other quantities. Since it is not realistic to expect that all end-users have installed switching devices that allow the change of connection phase, CS 3 in which the connection phase is randomly selected and remains the same during all time periods is introduced. In most cases end-users are not aware of the connection of their single-phase PV systems, therefore, CS 2 and CS 3 are the ones that most likely reflect a real-world situation. On the contrary, distribution system operators (DSOs) would like to prevent the random connection of single-phase PVs due to the possibility of an increase in network losses, voltage magnitude, or VUF values. For that reason, CS 4 and CS 5 are created. In CS 4, there is a possibility of changing the connection phase in different time periods, and a PV system is always connected to the phase with the highest demand. That way, the difference between the total demand of phases a, b, and c will be the lowest and the network will be the most balanced. The approach in CS 5 is more conservative and the change of demand phase is not possible. A PV system is connected to the phase with the highest daily demand. Even though this approach does not guarantee that the demand of a connection phase will be the highest in every time period, it is suitable for end-users that do not have installed phase-switching devices.

IV. Results

Analyses in all case studies are done using Python 3.9.16 programming language and the pyomo optimization framework [16]. The MINLP formulation in CS 1 is solved by the Knitro solver. Formulations in CS 2 - CS 5 are NLP without binary variables but knitro is also used in analyses. PC specifications are AMD Rzyen 5 3600 6-Core processor and 16.0 GB of RAM.

Table I summarizes the most important results of solving the optimization problem, values of the objective function and computational time for all case studies, and different constraints of the maximum PV power. When the maximum PV power is limited by the national grid code and is equal to $3.68kW$, the best value of the objective function is in CS 1 since it is the only case study in which the exact optimal solution of the given hosting capacity problem is guaranteed. However, the computational time is higher than one hour, but despite the long duration, the calculation of maximal daily PV production is in between the planning and operation problems and the computational time does not present an obstacle in using the MINLP model. Values of the objective function in CS 2-CS 4 are between 15 kWh and 1 kWh smaller than in CS 1. The results clearly show that removing binary variable and using an NLP model cause the loss of accuracy, but on the other hand, the computational time needed for solving the optimization problems are less than 2 minutes, which significantly reduces the computation burden and computation cost. The results are not unambiguous and it is up to system operators to determine what is more important, to have an exact solution, or to use randomization and approximation approaches that will lead to a faster solving of this and other similar optimization problems.

Since the second analysis assumes the maximum connection power of single-phase PVs to be 100 kW, non-static export limits higher than 3.68 kW are expected, i.e., maximum PV power will vary at different nodes in a network. Therefore, the difference between the optimal solution in CS 1 and solutions in CS 2-CS 5 is expected to be much more significant. However, the given MINLP problem is too computationally complex, and the time needed to find the optimal solution is higher than 3 days. Since the computational time that long is not feasible and the approach is non-scalable, optimization was terminated after running for three days and there is no solution in CS 1. The value of the objective function in CS 2-CS 5 varies between 2 542 kWh and 2 608 kWh, which is not a large interval of values considering the maximum connection power constraint. Computational time in CS 2, CS 4, and CS 5 is around 2.5 minutes, which is significantly less than the computational time in CS 1. Even though the computational time in CS 3 is also less than in CS 1, it is more than three times higher when compared to CS 2, CS 4, and CS 5. This shows the importance and the impact of the connection phase on the optimal solution of the optimization problem and also shows the reason for the long duration of solving the MINLP formulation in CS 1.

TABLE I
OPTIMIZATION RESULTS SUMMARY

	$(P^{PV})^{max} = 3.68kW$				
	CS 1	CS 2	CS 3	CS 4	CS 5
Objective function value (kWh)	893.87	878.72	892.60	882.22	889.41
Computational time (s)	3 737.00	104.20	104.80	105.58	105.46
	$(P^{PV})^{max} = 100kW$				
	CS 1	CS 2	CS 3	CS 4	CS 5
Objective function value (kWh)	—	2 607.58	2 542.79	2 608.35	2 543.85
Computational time (s)	>3 days	149.86	464.01	144.60	135.75

A more detailed analysis of optimization results includes analyses of active total daily network losses, voltage magnitude, and voltage unbalance. However, these analyses are conducted only for the first case in which the connection PV power is limited to 3.68 kW since the case of the increased connection power did not lead to the optimal solution within a reasonable time.

Fig. 2 shows the value of total daily network losses in CS 1-CS 5. As can be seen in the graph, the largest losses of 131.13 kWh occur in CS 1, when the daily production of PVs is calculated by using the MINLP formulation. Even though this solution leads to the maximization of production, it also increases the current that flows through lines due to the occurrence of reverse power flows. Losses in CS 2-CS 5 are in the range of 115.56-127.20 kWh and since the connection phase changes over case studies, the results show the correlation between the connection phase of a PV system and network losses. However, more general conclusions cannot be made without introducing stochasticity that allows defining multiple scenarios with different layouts of connecting PV systems.

Boxplots representing voltage magnitude are shown in Fig. 3. The upper bound of voltage magnitude is set to be 110% of the nominal voltage, and as it can be seen, this value is reached in all case studies, even though the values that high are identified as outlier values and occur rarely in comparison to the value in the interval 0.95 p.u.-1.05 p.u. The median value is around 0.99 p.u. and is almost the same in all case studies. Without considering outlier values, the minimum voltage magnitude in CS 1 is around 0.95 p.u. and around 0.96 p.u. in CS 2-CS 5. Maximum voltage values are in the range of 1.04 p.u.-1.06 p.u. The results show that even though the connection phase impacts voltage magnitude, values in the graph do not significantly vary in different case studies.

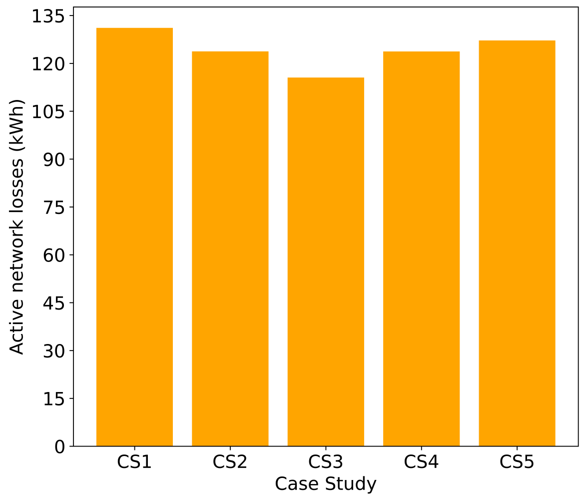

Fig. 2. Total daily active network losses - CS 1

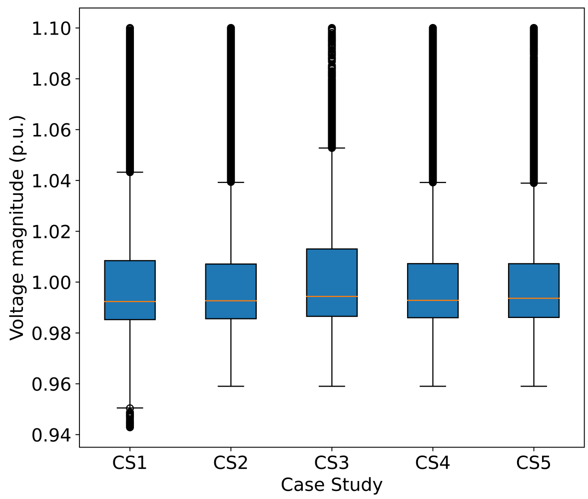

Fig. 3. Voltage magnitude - CS 1

Values of VUF are presented in Fig. 4. As it can be seen, values in the graph do not go higher than 1.6% and since the threshold VUF value is 2%, PV systems constrained by the connection power of 3.68 kW are not additionally constrained by voltage unbalance. Another interesting fact is the correlation of VUF with the value of network losses in CS 1-CS 5. When considering all values in a boxplot together with outlier values, the highest VUF occurs in CS 1 which corresponds to the value of network losses in the same case study. On the contrary, the lowest values of VUF and network losses are in CS 3. From these results, it is possible to determine a direct impact of voltage unbalance on network losses and to conclude that losses can be reduced by minimizing unbalance in a network.

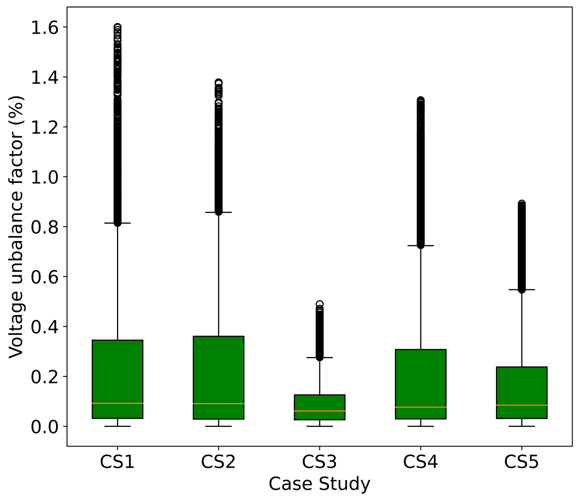

Fig. 4. Voltage unbalance factor - CS 1

V. Conclusion

The share of installed PV systems in LV networks is continuously increasing. There are numerous existing methods that focus on determining the PV hosting capacity and many of them are based on linearization or approximation optimization approaches that often lead to a sub-optimal solution. To overcome the problem, we use a non-linear OPF model in calculating the maximum daily production of single-phase PV systems. Additionally, we uplift the problem to the MINLP formulation, the only formulation that guarantees an exact, optimal solution to the given optimization problem. The MINLP formulation is used in two different cases, the first approach in which the PV system is constrained by the national grid code (3.68 kW) and the second approach in which connection power is constrained with a non-static limit. The computational time needed to solve the problem is higher than one hour in the first case, and in the second case optimization was terminated after it was not able to find the optimal solution for three days. To decrease the computational burden and decrease the duration of optimization, four different methods for determining the connection phase that do not use binary variables were used. The results show an expected decrease in the computational time and the loss of accuracy in terms of the objective function value. Moreover, a more detailed analysis of network losses, voltage magnitude, and voltage unbalance factor was conducted to further investigate the difference when using different approaches. Analyses show that the range of values of different quantities varies based on the observed case study, but differences are not significant and cannot be determined as obstacles in using one of the proposed NLP approaches.

Future work will focus on investigating scalability problems in optimization problems in three-phase LV networks. Problems include the introduction of stochasticity in hosting capacity problems, the use of linearized or approximated OPF models, but also considering other distributed energy resources in the optimization problem..

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Pp OPF - Pandapower Implementation of Three-phase Optimal Power Flow Model

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***Abstract*—Challenges in the planning and operation of distribution networks caused by the integration of distributed energy resources (DERs) create the need for the development of tools that can be easily used by system operators, industry, and the research society but are also easily upgraded with new functionalities. The full implementation of one such open source tool, named *pp OPF* (pandapower Optimal Power Flow), is presented in this paper. *Pp OPF* is the tool used for three-phase optimal power flow (OPF) calculations and it is based on already existing functionalities of pandapower, a Python library for power system calculations. The developed tool enables the possibility to use both power-voltage and current-voltage formulation in different OPF problems, such as determining the photovoltaic (PV) hosting capacity in three-phase distribution networks, the problem on which the functionality of the developed tool is tested. Additionally, the accuracy of *pp OPF* is verified by comparing the results with ones obtained by pandapower power flow calculation for the same set of input values. The open-source implementation allows further upgrades, the addition of new functionalities, and the creation of new case studies relevant to the planning and operation of distribution networks.**

***Index Terms*—distribution networks, distributed energy resources, pandapower, three-phase optimal power flow**

NOMENCLATURE

A. Sets and Indices

N	Set of all nodes
P	Set of all phases
T	Set of all time intervals
i, j	Begin and end node of the element, $i, j \in N$
n	Observed node, $n \in N$
$slack$	Slack node
p	Phase of the node, $p \in P$
t	$t \in T$

B. Parameters

$[Z_{012}]$	Sequence impedance matrix
$[A]$	Transformation matrix
$P_{i,p,t\ l}$	Active power of load l at phase p and in time period t
$Q_{i,p,t\ l}$	Reactive power of load l at phase p and in time period t
$U^{min/max}$	Minimum and maximum voltage magnitude
VUF^{max}	Maximum value of voltage unbalance factor
$S_{max,ij}$	Maximum apparent power of element ij

C. Variables

$U^{re/im}_{n,p,t}$	Real/imaginary part of voltage at node n, phase p, and in time period t
$P_{ij,p,t}$	Active power between nodes i and j, of phase p, and in time period t
$Q_{ij,p,t}$	Reactive power between nodes i and j, of phase p, and in time period t
$P_{n,p,t\ l/g}$	Active power of load l/generator g connected to the node n, phase p, in time period t
$Q_{n,p,t\ l/g}$	Reactive power of load l/generator g connected to the node n, phase p, in time period t

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I. INTRODUCTION

The share of low-carbon (LC) technologies has been continuously increasing. Despite the positive environmental and financial effects, the integration of LC units is often uncoordinated which can lead to different technical problems in the operation of distribution networks, including overvoltage and undervoltage [1], increased voltage unbalance [2], and overloading of lines and transformers [3].

Despite the high number of commercial software used for distribution networks analyses, recent digitization and more often exploitation of computing techniques in power systems planning and operation has led to the development of open source tools in high-level programming languages, such as MATPOWER [4] or pandapower [5]. These and similar tools are often used only for calculations of technical conditions in distribution networks and in most cases do not have implemented optimization techniques that can help in decision-making. As a way of battling these problems, the distribution system operators now more than ever reach for optimization tools as opposed to the conventional simulation-based approach, making optimal power flow algorithms essential in everyday operation.

Even though OPF models are well-known and widely used in different power system problems, e.g., unit commitment [6], their use in distribution and especially low voltage (LV) networks require modification and transition towards three-phase four-wire models. Three-phase OPF models have numerous applications, including optimal control of devices [7], congestion mitigation [8], calculation of operating envelopes [9], etc. Three-phase optimal power flow problems can be formulated as current-voltage [10] or power-voltage [11] and can be modeled as exact, non-convex problems [10] or they can be linearized [9] or relaxed [12].

Recent developments of open source software include the implementation of a three-phase OPF model as a Julia package [13] and integration of a three-phase OPF model with OpenDSS software [14]. Despite the recent developments in pandapower, including the creation of new elements and introduction of new functionalities, e.g., three-phase power flow and state estimation [15] or the availability of harmonic power flow simulations [16], using pandapower Python library in three-phase OPF problems is still not possible.

To overcome the detected pandapower shortfall, we propose an implementation of non-linear, current-voltage, and power-voltage three-phase OPF formulations using existing pandapower and newly added functionalities necessary for modeling the wanted problem. The developed tool named *pp OPF* (pandapower Optimal Power Flow) is open source and can be used by accessing [17]. The functionality of the tool is tested on the problem of calculating photovoltaic (PV) hosting capacity in a real-world LV network. The accuracy of the tool is verified against the results calculated by pandapower power flow simulations for the same input data. It is important to emphasize that the presented mathematical model and defined case study on which the model was tested are not novel contributions. However, to the best of the authors' knowledge, this is the first time that pandapower was used for the implementation of a three-phase OPF mathematical model. Additionally, problems that are solved by exact non-linear models are often non-scalable and require a significant computational burden in order to be solved. In this paper, an introduction to such problems and one possible method for overcoming them is presented next to the verification and the analysis of the case study results. *Pp OPF* is the only three-phase OPF tool that has been built upon the widely used Python library pandapower, and together with the development of Open-DSOPF presented in [14], it is the only publicly available Python-based tool that enables OPF simulations in three-phase distribution networks. As shown later in the paper, *pp OPF* is accurate, efficient, and provides a feasible solution, the same as OpenDS-OPF. Therefore, the selection of the tool for solving the given problems completely depends on the preferences of a user, but the presented development gives another option to researchers and the industry.

The rest of the paper is organized as follows: Section II presents the connection to pandapower by using some of the already developed functionalities. In Section III, the mathematical model of the power-voltage formulation is given. The results of a defined case study and the comparison of the results with ones obtained by pandapower are presented in Section IV, while the conclusions and future work are given in Section V.

II. Connection to pandapower

Pandapower is developed as an open source tool for power system modeling, analysis, and optimization with a high degree of automation. Since the new tool presented in this paper is used for analyses and optimization problems that have not yet been implemented in pandapower, the only existing functionality that is used is the modeling of distribution networks by using pandapower for defining different elements necessary for creating the representation of the observed distribution network, while all other necessary functions are built on top of that. Used elements are an external grid, transformers, lines, and loads. An external grid is used to define the per-unit voltage at the slack node. The assumption in the presented three-phase OPF model is that the voltage of the slack node is symmetrically distributed over phases, as shown in eq. (1).

$$\begin{aligned} U_{slack,a} &= U_{slack} \\ U_{slack,b} &= U_{slack}\angle-120^{\circ} \\ U_{slack,c} &= U_{slack}\angle 120^{\circ} \end{aligned} \tag{1}$$

Transformers are defined with parameters needed for the calculation of their impedance, such as voltage ratio, rated power, and short-circuit voltage. Lines are created with parameters including but not limited to resistance and reactance for zero and positive sequence systems, length, and maximum current. After creating these elements, already existing pandapower functionalities are used for calculating their impedance and placing them in the impedance matrix $\left[Z_{012}\right]$ containing the calculated impedance of zero, positive, and negative sequence systems. By using transformation matrix $\left[A\right]$ and its inverse $\left[A\right]^{-1}$, three-phase impedance matrix $\left[Z_{abc}\right]$ is calculated.

All loads in a distribution network are created using pandapower functionalities, together with other elements relevant to the representation of the network's mathematical mode. Since *pp OPF* is used in the multi-temporal optimization of three-phase power systems, loads need to be defined with the active and reactive power of each phase in each time period. Since the use of pandapower in multi-temporal simulations of a three-phase network is not straightforward, a load curve that defines the change of the loads' value during the observed period is additional input in the tool. Based on the objective function and the goal of the optimization problem, additional elements representing DERs such as PVs or electric vehicles (EVs) can be added to the formulation. These elements can be defined with a fixed value or can be defined as variables whose power needs to be determined during the solving of the defined problem.

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In order to integrate the presented tool with already existing pandapower functionalities, a Python script that creates all of the network's elements needs to be created first. After the creation of the pandapower model of a three-phase network, a script modifies the network data and creates three-phase impedance and admittance matrices. Finally, all mathematical equations and the constraints valid for both current-voltage and power voltage formulations of the three-phase OPF model are integrated into two final scripts. A user of the tool is only responsible for the creation of the mathematical model of a network, in a same way as in the case of using pandapower, i.e., there is no need for additional effort since the functionalities of the OPF model are developed as a part of the source code.

III. Three-phase OPF mathematical model

After defining a three-phase distribution network with all of its elements using pandapower, its parameters are used in the developed OPF formulation. The *pp OPF* tool integrates both power-voltage and current-voltage formulations. OPF models are formulated using Python programming language and Pyomo optimization framework. However, in this paper, only the mathematical model of a power-voltage formulation is presented, while both formulations are tested and verified on case studies presented in Section IV.

Active and reactive power flow between nodes i and j is described with eqs. (2) and (3). Additionally, the power flow through each element cannot be larger than the maximum power which is defined as an input parameter of a transformer or a line in the observed network. This constraint is given with eq. (4).

$$\begin{aligned} P_{ij,p,t} = &\sum_{q\in\{a,b,c\}} (U^{re}_{i,p,t} \cdot U^{re}_{i,q,t} + U^{im}_{i,p,t} \cdot U^{im}_{i,q,t}) \cdot G_{ij,pq} + \\ &\sum_{q\in\{a,b,c\}} (U^{im}_{i,p,t} \cdot U^{re}_{i,q,t} - U^{re}_{i,p,t} \cdot U^{im}_{i,q,t}) \cdot B_{ij,pq} - \\ &\sum_{q\in\{a,b,c\}} (U^{re}_{i,p,t} \cdot U^{re}_{j,q,t} + U^{im}_{i,p,t} \cdot U^{im}_{j,q,t}) \cdot G_{ij,pq} - \\ &\sum_{q\in\{a,b,c\}} (U^{im}_{i,p,t} \cdot U^{re}_{j,q,t} - U^{re}_{i,p,t} \cdot U^{im}_{j,q,t}) \cdot B_{ij,pq} \end{aligned} \tag{2}$$

$$\begin{aligned} Q_{ij,p,t} = -&\sum_{q\in\{a,b,c\}} (U^{re}_{i,p,t} \cdot U^{re}_{i,q,t} + U^{im}_{i,p,t} \cdot U^{im}_{i,,tq}) \cdot B_{ij,pq} + \\ &\sum_{q\in\{a,b,c\}} (U^{im}_{i,p,t} \cdot U^{re}_{i,q,t} - U^{re}_{i,p,t} \cdot U^{im}_{i,q,t}) \cdot G_{ij,pq} + \\ &\sum_{q\in\{a,b,c\}} (U^{re}_{i,p,t} \cdot U^{re}_{j,q,t} + U^{im}_{i,p,t} \cdot U^{im}_{j,q,t}) \cdot B_{ij,pq} - \\ &\sum_{q\in\{a,b,c\}} (U^{im}_{i,p,t} \cdot U^{re}_{j,q,t} - U^{re}_{i,p,t} \cdot U^{im}_{j,q,t}) \cdot G_{ij,pq} \end{aligned} \tag{3}$$

$$P^{re\ 2}_{ij,p} + Q^{im\ 2}_{ij,p} \leq S_{max,ij} \tag{4}$$

Besides power flow, the only other constraint needed in the power-voltage formulation is Kirchoff's Current Law (KCL) presented with active and reactive power instead of current. For securing KCL, the following eqs. (5) and (6) are defined.

$$P_{i,p,t\ g} + P_{h\to i,p,t} = P_{i,p,t\ l} + P_{i\to j,p,t} \tag{5}$$

$$Q_{i,p,t\ g} + Q_{h\to i,p,t} = Q_{i,p,t\ l} + Q_{i\to j,p,t} \tag{6}$$

Equations used for constraining values of voltage magnitude and voltage unbalance factor (VUF) are presented with eqs. (7) and (8).

$$(U^{min})^2 \leq (U^{re}_{i,p,t})^2 + (U^{im}_{i,p,t})^2 \leq (U^{max})^2 \tag{7}$$

$$\frac{|U_{n,a} + a^2 \cdot U_{b,n} + a \cdot U_{c,n}|^2}{|U_{n,a} + a \cdot U_{b,n} + a^2 \cdot U_{c,n}|^2} \leq (VUF^{max})^2 \tag{8}$$

IV. PVs hosting capacity

PVs or other DERs in general can be single-phase or three-phase connected to the network. Single-phase connection is easier and cheaper at the LV level but is limited with relatively low export or import power, e.g., export power in Croatian LV networks may not be higher than 3.68 kW [18], and can lead to the increase in voltage unbalance. On the contrary, a three-phase connection allows the installation of PVs with higher production power and solves the unbalance problem but the connection is more expensive and complex.

In this paper, two case studies are defined for calculating the hosting capacity of PVs (generators g) in a real-world LV distribution network. In the first case study, PVs can only be single-phase connected to one phase at a time, and in the second, PVs are three-phase connected to the network. To obtain an exact, optimal solution, the presented formulation needs to be extended with binary variables that will define the exact connection phase in the case of a single-phase connection or if PVs are single-phase or three-phase connected at a certain node. Such an approach would uplift the formulation from the non-linear programming (NLP) problem to the mixed-integer (MI)NLP problem, which would lead to problems related to the scalability and the computational time needed for finding an optimal solution. Therefore, both case studies are defined as NLP problems and solved using the pyomo optimization framework and the ipopt solver. In the case of a single-phase connection of PVs, their connection phase is randomly pre-defined in each node. When a three-phase connection is observed, the power of PVs is distributed over the phases and PVs can not be single-phase connected. In cases of well-built and resilient networks, determining the hosting capacity will mostly lead to the connection of PVs with the larger connection power, which makes the assumption that PVs are always three-phase connected valid in solving the presented problem. In both observed case studies, the production power of PVs is constrained with the curve containing per-unit values scaled according to the largest measured value of production in the observed network's location, as shown in eq. (9).

$$P_{n,p,t\ PV} \leq P_{PV,max} \cdot P_{PV,t} \tag{9}$$

where $P_{n,p,t\ PV}$ is the variable representing the calculated power of PV at the certain node n, phase p, and time period t, $P_{PV,max}$ is the theoretical maximum value of PVs production, and $P_{PV,t}$ is the per-unit value that ensures the value of production that does not exceed the limit defined by the irradiation and other physical quantities.

For the presented case study, a real-world Croatian LV network shown in Fig. 1 was created using pandapower. Additionally, measurements collected from the smart meters were used to define the values of the loads' active and reactive power.

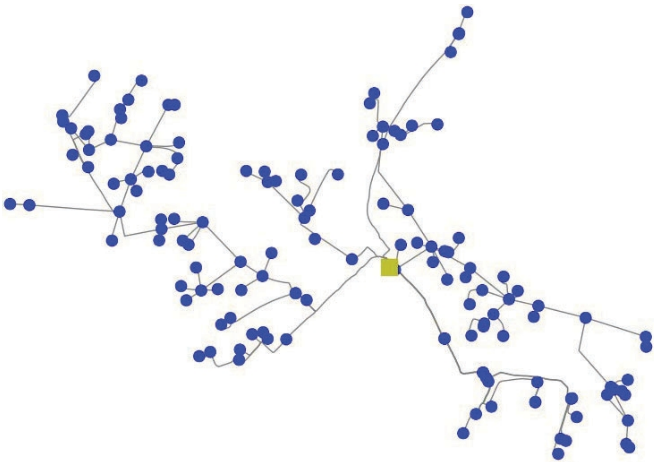

Fig. 1. A residential LV network

Fig. 2 shows the summarized PV production curve for each phase over time in the first case study. The curve has the shape characteristic for the production of PVs, with the characteristic distortions caused by sudden weather changes that affect the production power. Together with the shape, values in the PV production curve are similar every day, with a maximum power of almost $120kW$. The calculated value of the objective function is equal to the theoretical maximum, i.e., a different selection of PV connection phases would not lead to additional generation and the use of the NLP instead of MINLP formulation does not cause the loss of accuracy. However, a different network topology or a change of the objective function could change that and show the need for using the exact MINLP formulation. A more detailed investigation of that problem is out of the scope of the paper.

In the second case, PVs were three-phase connected to the network. Fig. 3 does not show the power of each phase but only cumulative power at each node, since the production power at every phase is almost the same. The results show that the three-phase connection allows the significantly higher capacity of installed PVs in the same network, with the production power at several time periods of almost $3500kW$. The results also confirm and make valid the assumption that none of the PVs are single-phase connected, which is relevant in avoiding MINLP formulations of a given problem.

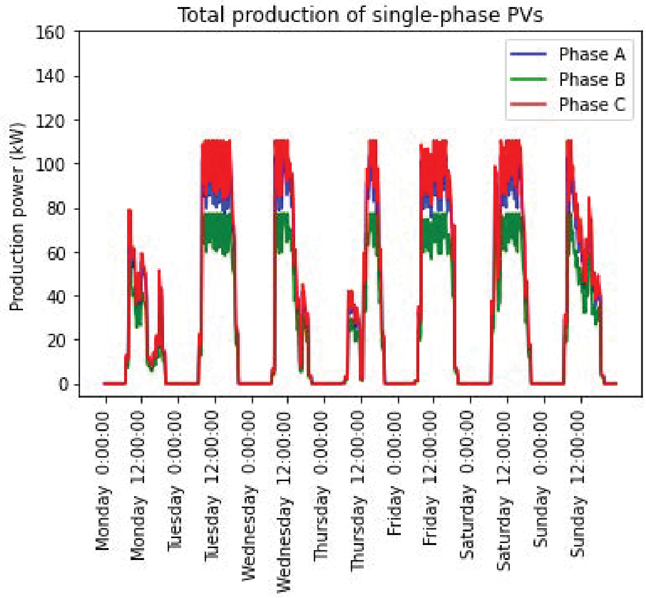

Fig. 2. Production of single-phase PVs

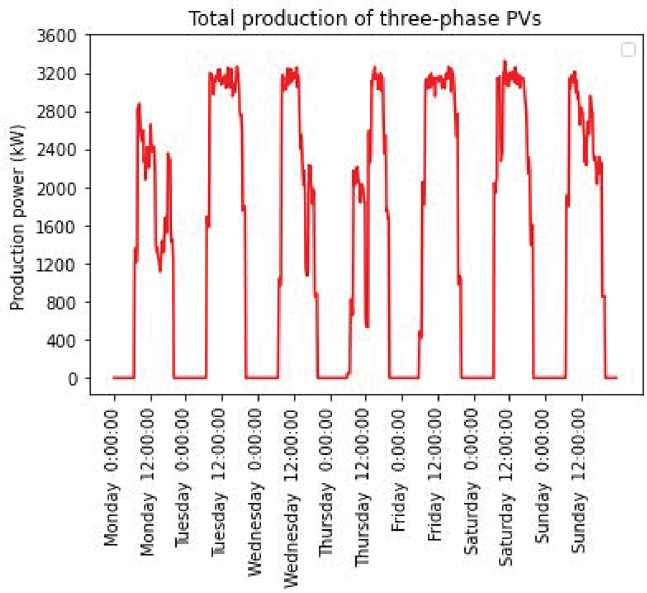

Fig. 3. Production of three-phase PVs

The results clearly indicate that in order to maximize the share of LC units, a three-phase connection should be encouraged but a detailed study on finding the optimal location and size of PVs in the network is outside the scope of the paper. Moreover, it is already well-investigated in the existing literature. The main goal of this paper was to test the functionality of the implemented tool on one possible example. Additionally, the presented case study is used as an

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introduction to the potential methods that can be used in the improvement of the scalability of the problems solved using three-phase OPF formulations.

Since both current-voltage and power-voltage formulations are implemented from scratch, it is necessary to verify the results of OPF calculations. Verification is made by comparing the results obtained by the *pp OPF* with the results obtained by pandapower PF calculation for the same network and set of values. One of the outputs of the presented tool *pp OPF* is the power of a single-phase or three-phase generator connected to a node. Together with the technical parameters of an LV network and active and reactive power of end-users' demand, the power of generators is used as input in the pandapower power flow calculation. Therefore, voltage magnitude values are calculated by two different tools for the same conditions, which enables the comparison of the results. Table I shows the comparison of voltage magnitude calculated with *pp OPF* and pandapower.

TABLE I
COMPARISON OF RESULTS: PANDAPOWER AND *pp OPF*

	Maximum error (p.u.)	Minimum error (p.u.)	Average error (p.u.)	Median error (p.u.)	RMSE (p.u.)
Current-voltage formulation	0.0624	0.0000	0.0024	0.0000	0.0086
Power-voltage formulation	0.0472	0.0000	0.0074	0.0055	0.0097

As it can be seen from the comparison, neither of the calculated errors is of a significant value, with the maximum error lower than 0.07 p.u., which can be characterized as an outlier value and with even lower values of other calculated deviations. Calculated differences clearly indicate that the presented tool can be used in different problems in three-phase distribution networks.

V. CONCLUSIONS AND FUTURE WORK

In this paper, we present the development and implementation of *pp OPF*, a three-phase OPF-based tool presented in this paper. *pp OPF* is developed as an extension of pandapower, an already developed open source tool for power system simulations. Both power-voltage and current-voltage OPF formulations were added on top of existing pandapower functionalities.

Following the development and implementation, *pp OPF* has been verified and tested on the real-world case study. In the defined case study, a real-world three-phase LV network was used in order to calculate its PV hosting capacity, both in cases of single-phase and three-phase connection of PVs. The results of the simulation were expected and emphasize the need for the encouragement of a three-phase connection or relaxing the limitations of a single-phase connection. A more detailed analysis of the results is outside the scope of this paper since the main objective was to present one of the potential functionalities of the developed tool.

The results of the comparison show that there are no significant differences between voltages calculated by the two different tools, with the maximum error detected as an outlier value and together with the values of other calculated errors, it clearly shows that there are no obstacles in using the *pp OPF* tool in calculating PV hosting capacity and other optimization problems in three-phase distribution networks.

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The Importance of Technical Distribution Network Limits in Dynamic Operating Envelopes

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***Abstract*—End-users more often decide to invest in distributed generation (DG) units that help them in decreasing electricity bills and allow them to become a market player by selling the excess produced electricity. However, the installation of DG is often limited by technical constraints of the network, standards, and national grid codes. As a method for removing the mentioned obstacles, the potential of dynamic operating envelopes (DOEs) is recently becoming recognized as a way for maximizing the benefits of installing DG. In this paper, we present an improvement of the already developed models that often neglect voltage unbalance constraints or are not based on an optimization approach. To test the model, two realistic case studies are defined. The results show that not all technical constraints are equally important, that the voltage unbalance constraint impacts the calculated DOEs for single-phase installed DG units, and that neglecting the temporal and spatial component in determining the limitation power is inadequate.**

***Index Terms*—dynamic operating envelopes, low voltage networks, optimal power flow, technical constraints**

I. Introduction

Dynamic operating envelopes (DOEs) are a concept that has been proposed to allow distribution utilities to move away from static limits for distributed energy resources connecting to the distribution grid, thereby enabling the energy transition by allowing more renewable generation [1]. In Australia, there is growing momentum to enable flexible customer connections, with DOE calculation engines determining connection capacities in real-time [2]. By freeing up additional network capacity, DOEs provide consumers with equitable access, improving on the inherently conservative nature of static export limits. DOEs are typically envisioned to provide ranges of feasible import/export values – *not set points* – at the customer connection level and are generally conceived to be physics-informed and explainable, with appropriate representation of technical limits of the system [3].

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The work in this paper is exploratory and is not representative of GridQube's commercial offerings in this space.

Table I develops a comparison of key publications related to the development of DOE calculation engines, with a variety of approaches being taken. Certain papers focus on the case of active power exports only, however there seems to be a trend to consider both import and export limits for both active and reactive power. The network model detail also varies between publications, with some of the papers using a balanced (a.k.a. positive sequence) model of the network impedances (size of the Z matrix is 1x1), others using sequence parameterization (positive, negative and zero sequence values are used to create 3x3 phase-coordinate impedance matrix) and others support a three-phase explicit-neutral representation (up to 4x4 as derived from the modified Carson's equations). Papers represent a variety of network limits in power, voltage and/or current, however voltage unbalance limits are rarely discussed, despite them being part of standards of supply in public distribution networks.

There are two main ways authors approach the calculation of the DOE values: either optimization-based or an iterative approach evaluating an existing power flow solver. The optimization-based approaches are typically custom, being either proprietary or extending toolboxes such as PowerModelsDistribution [4] or *pp OPF* [5]. Iterative approaches [6], [7] can leverage commercial software to solve the power flows, which may also avoid conversion of network data formats. However, getting access to derivatives in commercial software is generally not supported, which makes it hard to build efficient optimization approaches that can assert the optimality conditions.

Exact optimization models for power networks with variables for complex power are inevitably nonlinear and nonconvex. Due to perceived scalability issues, many authors shy away from developing nonlinear programming models, and instead develop a linearized model of the physics to pass on to linear programming solvers [9]–[12], [14], [16].

Neglecting phase unbalance leads to very optimistic estimates of import and export limits, that will not be achievable in the field. Linearized power flow formulations such as LinDist3Flow [17] only have variables for voltage magnitude and do not include voltage unbalance factor (VUF) limitations.

TABLE I: Scope of different research outputs focusing on DOEs

Reference	Z size	P/Q?	import/export	optimization-based?	Remarks
Blackhall, 2020 [8]	1x1			(agnostic)	Design discussion
Petrou et al., 2020 [9]	3x3	P	both	✓	Linearization
Liu B. & Braslavsky, 2020 [10]	3x3	P	both	✓	Linearization, robust uncertainty
Liu M. et al., 2022 [11]	3x3	P+Q	both	✓	Linearization
Liu M. et al., 2021 [12]	3x3	P	export	✓	Linearization
Bassi et al., 2022 [13]	3x3	P	both	✗	Model-free
Yi & Verbič, 2022 [14]	1x1		export	✓	Convex relaxation, explicit uncertainty
Ochoa et al., 2022 [15]	3x3	P+Q	both	✓	Conceptual
Gerdroodbari et al., 2022 [6]	4x4	P+Q	both	✗	Iterative using PF solver
Milford & Krause, 2021 [16]	4x4	P	both	✓	Linearized in state estimation solution
Project EDGE, 2022 [7]	(?)	P+Q	both	✗	Iterative using PF solver/heuristics
Antić et al.	3x3	P+Q	export	✓	Exact, nonlinear, nonconvex

Nonlinear models are nevertheless capable of representing all the limits without approximation. Neglecting network losses, e.g. in LINDIST3FLOW, leads to voltage magnitude accuracy problems [17], as the power needed to supply the losses does not cause an additional voltage drop due to the linearization. Linearization can help scaling up optimization models that consider uncertainty though, which has recently been explored in [10], [14].

We conclude that there is a gap in the literature on optimization-based DOE calculation using exact *nonlinear* models of the *unbalanced* distribution network. Papers frequently also ignore voltage unbalance metrics such as VUF. To overcome the identified research gap, following contributions are proposed:

- In this paper, we explore the impact of different technical constraints on the values calculated for DOEs, including a transformer's and lines' current and voltage magnitude and unbalance constraints
- The exact nonlinear physics without approximation, with an unbalanced model of an LV network is used in the DOEs calculation.
- We illustrate the impact on two case studies of real-world network datasets.

Note that *we do not design DOE calculation procedures in this work*, but instead focus on exploring the application of technical limits that influence import/export values derived by such approaches in a LV network context.

The rest of the paper is organized as follows: An exact mathematical model used in the calculation of DOEs is presented in Section II. Case studies with the descriptions of a Croatian and Australian LV network used in calculations are defined in Section III, while definition of scenarios and the results of calculation are shown in Section IV. Finally the conclusions are given in Section V.

II. MATHEMATICAL FORMULATION

The calculation of the export DOEs presented in this paper is based on the non-convex three-phase current-voltage OPF formulation, without relaxation or linearization using the modification of *pp OPF*, the tool presented in [5].

Calculation of the real and imaginary part of the voltage drop across all phases p for a branch l connecting buses i and j can be represented with eqs. (1) and (2).

$$U^{re}_{j,p,t} = U^{re}_{i,p,t} - \sum_{q\in\{a,b,c\}} R_{l,pq} \cdot I^{re}_{l,ij,q,t} + \sum_{q\in\{a,b,c\}} X_{l,pq} \cdot I^{im}_{l,ij,q,t} \tag{1}$$

$$U^{im}_{j,p,t} = U^{im}_{i,p,t} - \sum_{q\in\{a,b,c\}} R_{l,pq} \cdot I^{im}_{l,ij,q,t} - \sum_{q\in\{a,b,c\}} X_{l,pq} \cdot I^{re}_{l,ij,q,t} \tag{2}$$

Active and reactive power in branch l flow from node i to node j are constrained with eqs. (3) and (4).

$$P_{l,ij,p,t} = U^{re}_{i,p,t} \cdot I^{re}_{l,ij,p,t} + U^{im}_{i,p,t} \cdot I^{im}_{l,ij,p,t} \quad \forall(l,i,j) \tag{3}$$

$$Q_{l,ij,p,t} = U^{im}_{i,p,t} \cdot I^{re}_{l,ij,p,t} - U^{re}_{i,p,t} \cdot I^{im}_{l,ij,p,t} \quad \forall(l,i,j) \tag{4}$$

Since the presented model is defined as a current-voltage formulation, it is necessary to calculate real and imaginary part of currents caused by nodal demand d and generation g, as shown in eqs. (5) and (6).

$$P_{g/d,p,t} = U^{re}_{i,p,t} \cdot I^{re}_{g/d,p,t} + U^{im}_{i,p,t} \cdot I^{im}_{g/d,p,t} \quad \forall(g/d,i) \tag{5}$$

$$Q_{g/d,p,t} = U^{im}_{i,p,t} \cdot I^{re}_{g/d,p,t} - U^{re}_{i,p,t} \cdot I^{im}_{g/d,p,t} \tag{6}$$

Finally, in order to ensure Kirchoff's Current Law (KCL), for both real and imaginary part, eq. (7) is introduced.

$$I^{re/im}_{d,i,p,t} - I^{re/im}_{g,i,p,t} - I^{re/im}_{l,h\to i,p,t} + I^{re/im}_{l,i\to j,p,t} = 0 \tag{7}$$

Eq. (8) is the expression for constraining the value of the line l current, while eq. (9) and eqs. (10)-(12) are the common expressions used for constraining the values of voltage magnitude and voltage unbalance factor. Maximum values of current are defined as parameters of input data, i.e., each line in both the Croatian and Australian case study has the predefined fixed value of the allowed current. In both Australian and Croatian low voltage networks, the maximum value of voltage U^{max} is equal to 1.1 p.u. Minimum voltage U^{min} in the Australian LV grid is equal to 0.94 p.u., while in the Croatian case, it is equal to 0.9 p.u. Maximum values of VUF are equal to 2%, which is the threshold defined in national grid codes and other relevant standards.

$$(I^{re}_{l,ij,p,t})^2 + (I^{im}_{l,ij,p,t})^2 \leq (I^{max}_{l,ij})^2 \tag{8}$$

$$(U^{min})^2 \leq (U^{re}_{i,p,t})^2 + (U^{im}_{i,p,t})^2 \leq (U^{max})^2 \tag{9}$$

$$\frac{|U_{2,n}|^2}{|U_{1,n}|^2} \leq (VUF^{max}_n)^2 \tag{10}$$

$$|U_{2,n}|^2 = [U_{a,n}^{re} - \frac{1}{2} \cdot (U_{b,n}^{re} + U_{c,n}^{re}) + \frac{\sqrt{3}}{2} \cdot (U_{b,n}^{im} - U_{c,n}^{im})]^2 + [U_{a,n}^{im} - \frac{1}{2} \cdot (U_{b,n}^{im} + U_{c,n}^{im}) - \frac{\sqrt{3}}{2} \cdot (U_{b,n}^{re} - U_{c,n}^{re})]^2 \quad (11)$$

$$|U_{1,n}|^2 = [U_{a,n}^{re} - \frac{1}{2} \cdot (U_{b,n}^{re} + U_{c,n}^{re}) - \frac{\sqrt{3}}{2} \cdot (U_{b,n}^{im} - U_{c,n}^{im})]^2 + [U_{a,n}^{im} - \frac{1}{2} \cdot (U_{b,n}^{im} + U_{c,n}^{im}) + \frac{\sqrt{3}}{2} \cdot (U_{b,n}^{re} - U_{c,n}^{re})]^2 \quad (12)$$

In the first case, the only objective is to maximize the sum of active power of all generators g connected to a network over time periods t, as shown in eq. (13). Reactive power is defined as a variable but its value is not observed within the objective function.

$$\max \sum_{t \in T} \sum_{i \in N_g} P_{g,p,t} \quad (13)$$

This objective is to be interpreted as the maximum simultaneous export of DGs, with the optimized maximum values defining the export limits for the customers. In reality, distribution utilities may deviate from this objective to make the assignment of export capacity more fair.

In the second case, we only maximize the reactive power margins. We introduce two variables to represent the import/export of reactive power separately:

$$Q_{g,p,t} = Q_{g,p,t}^{+} - Q_{g,p,t}^{-}, \quad Q_{g,p,t}^{+}, Q_{g,p,t}^{-} \geq 0 \quad (14)$$

We introduce an auxiliary variable $Q_{g,p,t}^{aux}$.

$$Q_{g,p,t}^{aux} \leq Q_{g,p,t}^{-}, \quad Q_{g,p,t}^{aux} \leq Q_{,p,t}^{+}, \quad Q_{g,p,t}^{aux} \geq 0 \quad (15)$$

And define the objective with eq. (16),

$$\max \sum_{t \in T} \sum_{i \in N_g} Q_{g,p,t}^{aux}. \quad (16)$$

III. Case studies

In order to exclude the results and conclusions that are tested on synthetic, benchmark networks or are valid for only one certain case, case studies are defined for Croatian and Australian LV networks, that are characterized with different layouts, technical parameters of network elements, and end-users' consumption. Defined case studies used in simulations and the calculation of DOEs are:

- Case study 1 - Croatian LV network
  1a)Objective function is defined with eq. (13)
  1b)Objective function is defined with eqs. (14)-(16)
- Case study 2 - Australian LV network
  2a)Objective function is defined with eq. (13)
  2b)Objective function is defined with eqs. (14)-(16)

In our case studies we consider the load to be fixed and unsheddable. Therefore we focus on maximizing export instead.

A. Croatian LV Network

Croatian LV networks are 3-phase 4-wire networks and depending on the part of Croatia, they are mostly constructed with underground cables in urban parts and with overhead lines in rural parts of the country. An LV network used in simulations is an urban network with 65 nodes, an MV/LV transformer, and 63 cables, defined with their positive and zero sequence resistance and reactance, which are then used in calculating the three-phase impedance matrix of a network.

In a network defined in the Croatian case study, there are 43 three-phase connected end-users, and their phase consumption curves are created from the measurements collected from smart meters. In the case study in this paper, all distributed generators (DGs) are observed as single-phase with a randomly selected connection phase in each node.

B. Australian LV Network

We choose network 'N' from the public data release of the CSIRO LV feeder taxonomy project [18], and use the improved impedance data proposed in [19]. This Australian network is a 3-phase 4-wire with a multigrounded neutral overhead backbone, with aerial bundled conductors for the service line (between the feeder and the house). Kron's reduction of the neutral has been performed throughout. A modeled Australian LV network consists of 99 LV nodes and 98 cables.

End-users are connected to 63 nodes, and 62 of them are single-phase connected to a network, while only one is connected three-phase. Same as in the Croatian case study, the consumption curve for each end-user is created from real-world smart meter data. In the Australian case study, DGs are single-phase connected, to the same phase as end-users.

IV. Scenarios and results

The main goal of the presented idea is to show the importance of different technical constraints in calculating DOEs in LV distribution networks. By defining different scenarios, it is possible to assess the value of each technical constraint and their contribution to calculating export DOEs in LV networks but also to identify the shortcoming in already existing approaches that neglect constraints such as current or unbalance constraints. Five defined scenarios include different sets of technical limits:

1) DG production is constrained by the limitations defined by the Croatian (3.68 kVA) and Australian grid code (5 kVA/phase)
2) Voltage magnitude and unbalance constraints are considered while transformer's and lines' current constraints are neglected
3) Voltage and current grid constraints are considered while the voltage unbalance constraint is neglected
4) Current magnitude and voltage unbalance constraints are considered while the voltage magnitude constraint is neglected
5) All constraints are considered (voltage and current magnitude, voltage unbalance)

Scenario 1 is defined to compare the possibility of installation of DGs according to current standards which need to be satisfied for system operators to allow the installation. Scenario 2 is chosen to determine the error of models that neglect current constraints. Most of the papers neglect the voltage unbalance constraint and the authors in general do not consider its value in the calculation of DOEs. To overcome this shortcoming, we identified Scenario 3. Even though the voltage magnitude constraints are always considered in already developed models, it is hard to assess its value compared to other technical constraints. Therefore, we define Scenario 4. Finally, Scenario 5 is the one in which all constraints are considered to use a more precise model. Defining multiple scenarios allows the assessment of the value of different network constraints in the context of calculating dynamic operating envelopes.

Table II is given as a brief summary of the DOEs calculation for both Croatian and Australian case studies. Active production in cases 1a) and 2a) emphasizes the need for implementing DOEs and abandoning traditional approaches in which production power is limited without considering the network conditions. In scenarios 3-5, daily production is larger by more than 2 MWh compared to Scenario 1, which is limited by the national grid codes. The production is even larger in Scenario 2 in which the current constraint is neglected. Due to the increase in values of active and reactive power, the such approach brings values of voltage magnitude close to the bounds but also increases the current flow which is multiple times higher than any feasible, possible solution. These results present a warning for models that rely on a correlation between the values of nodal voltages and power instead of on a detailed model of a network.

The change of the objective function in cases 1b) and 2b) causes a decrease in the daily production in both the Croatian and Australian case studies. The used modeling approach gives values of reactive power production that are close to zero. With a such set of values of DGs' reactive power, daily active production is between 3 and 4 MWh lower than in cases 1a) and 2a). Active production in scenarios 3-5 is even smaller than the potential production constrained only by the national grid codes. In the Croatian case study, the value of production in Scenario 2 in which the current constraint is neglected is more than 1 MWh smaller than in Scenario 1, which only shows the importance of unbalance constraint in some network topologies and highlight the flaws of approaches that neglect it.

A. Case Study 1

Fig. 1 shows the results of the calculation in case 1a), when the objective function is to maximize the sum of the active power of all generators. The importance and necessity of considering different technical constraints in case 1a) can be seen in Fig. 1 which shows the change of production in each time period for each scenario. The largest production power of DGs is in Scenario 2, the one in which current constraints are neglected, similar to model-free approaches.

TABLE II: Potential daily production of DGs for different scenarios

	Total production (kWh)			
	1a)	1b)	2a)	2b)
Scenario 1	3 797.76	3 797.76	7560.00	7 560.00
Scenario 2	63 348.53	2 578.36	123 219.27	23 262.20
Scenario 3	6 230.82	2 343.95	9 578.21	5 859.42
Scenario 4	6 623.02	3 522.97	9 654.57	5 794.44
Scenario 5	6 108.92	2 380.36	9 592.73	5 833.06
	Total production (kVArh)			
	1a)	1b)	2a)	2b)
Scenario 1	0.00	0.00	0.00	0.00
Scenario 2	-16 506.63	0.00	-71 650.03	0.00
Scenario 3	627.76	0.00	879.63	0.00
Scenario 4	743.01	0.00	1 054.44	0.00
Scenario 5	660.04	0.00	940.27	0.00

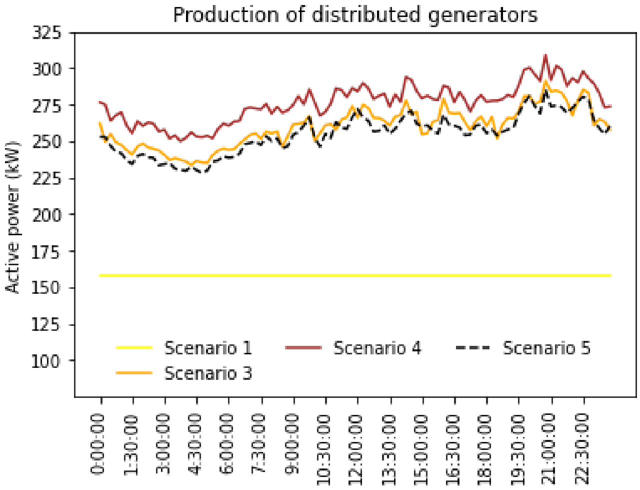
However, a significant decrease in production power in other scenarios clearly shows the shortcoming of such approaches. Additionally, commonly used models that neglect voltage unbalance are inadequate since the additional consideration of unbalance (Scenario 5) further limits the production of DGs compared to the scenario in which only this constraint is neglected (Scenario 3). The results in Scenario 5 clearly show the need of abandoning the concept in which the limitation of DGs connection power is constant since based on a network's layout and end-users' consumption production curve changes and is always larger than defined limitation.

Fig. 2 shows the results for the Croatian case study 1b) when the objective function is the maximization of the reactive power margins. Defining additional constraints in the mathematical model used in case 1b) limits the active production in the observed network and for most scenarios and time periods even decreases it below the limitation defined by the Croatian grid code (Scenario 1).

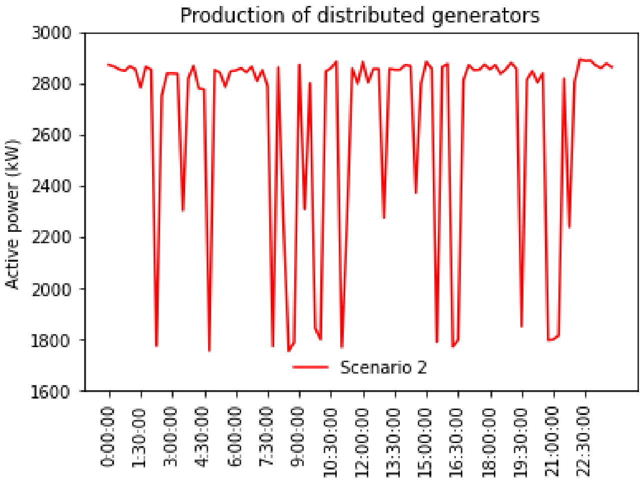
Furthermore, the results in the graph additionally emphasize the need of modeling all technical constraints as in Scenario 5, since they lead to a decrease in active production. Production in scenarios 3, 4, and 5 are lower than in case 1a) but with a similar shape of the DOE curve, unlike production in Scenario 2 which not only significantly decreased but the shape of the curve changed and the drops that previously existed do not occur.

B. Case Study 2

Fig. 3 shows the results of the DOEs calculation for the Australian case study 2a). The conclusions drawn are similar to those in the Croatian one, with the exception of an even larger decrease in DGs' production power in scenarios in which the current constraint is considered. Also, the range between the upper and lower bound of production power in scenarios 3-5 is larger in the Australian case study which can be correlated with a difference in consumption profiles but also the difference in the network's layout. Another significant importance compared to a Croatian case study is the smaller impact of modeling different constraints on the optimal solution of the presented problems, with the same reasons as for the larger range of active production power values.



(a)



(b)

Fig. 1: Calculated export DOEs - Case Study 1a

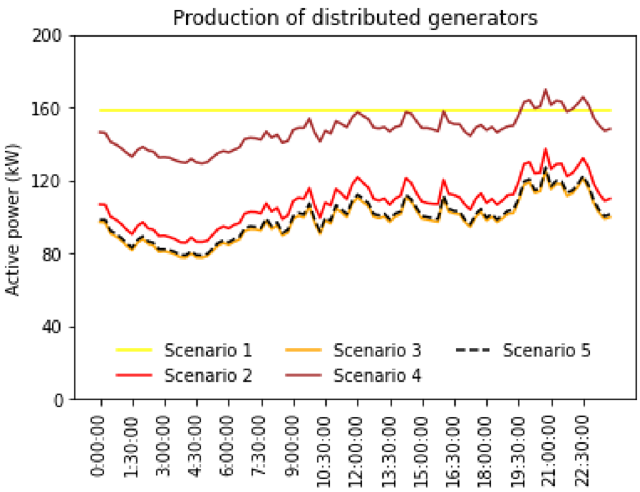
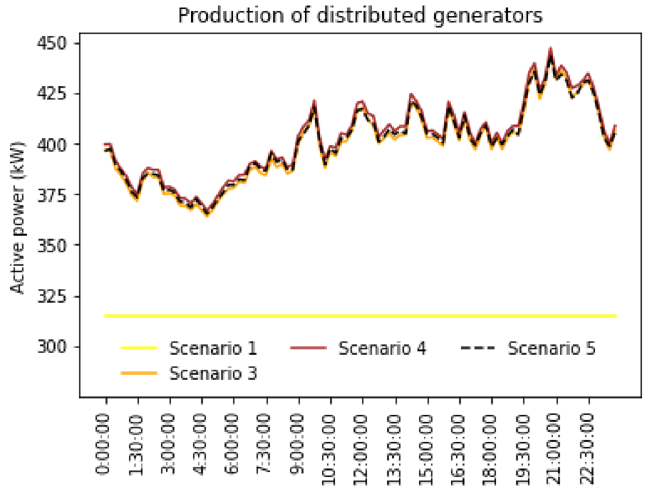


Fig. 2: Calculated export DOEs - Case Study 1b



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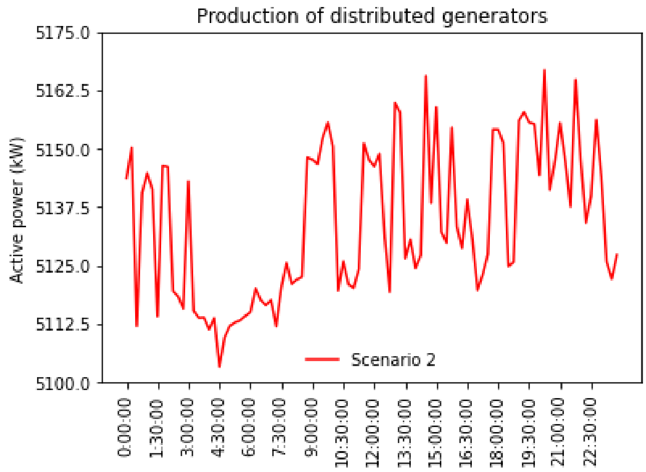
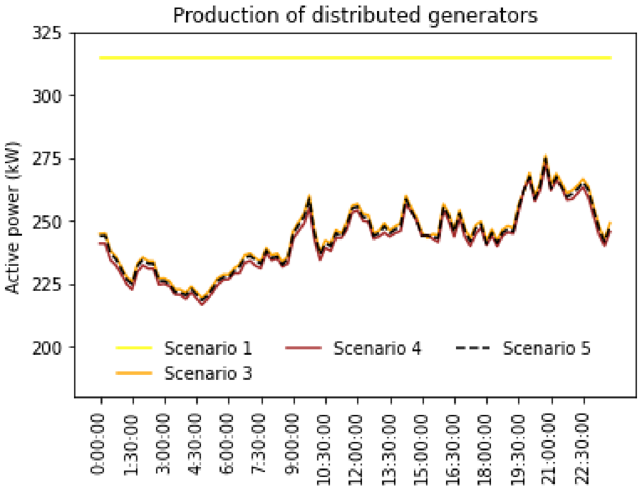


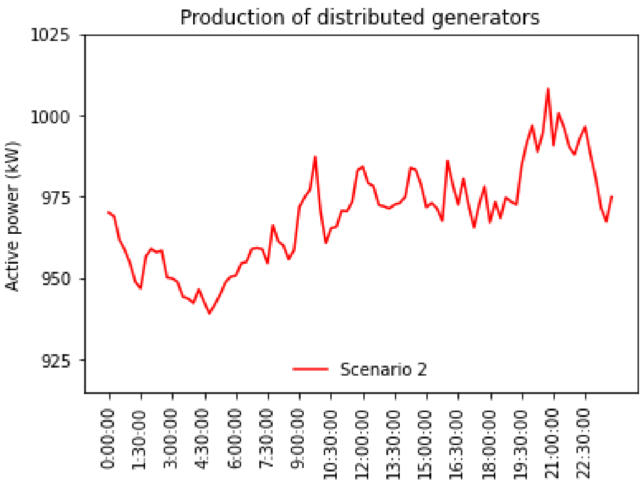
(b)

Fig. 3: Calculated export DOEs - Case Study 2a

The calculation of DOEs in case study 2b) is shown in Fig. 4. According to the results, the change of the objective functions leads to limiting the active production of DGs below the value defined by the Australian grid code. Also same as in the first Australian case 2a), the impact of different technical constraints on values in the graph is not as significant as in Croatian cases. Active production in Scenario 2 is multiple times higher than production in other scenarios, the same as in the Australian case 2a). An interesting point is that in the Croatian case 1b), in which the objective function is the same as in case 2b), this difference does not exist meaning that the threshold value of voltage unbalance is reached before the value of active power increases enough to lead to high currents in an observed grid. This emphasizes the need for precise modeling but also shows a difference caused by observing two network topologies with non-similar characteristics.



(a)



(b)

Fig. 4: Calculated export DOEs - Case Study 2b

V. Conclusions

This paper explored the application of different network limits in the context of potential dynamic operating envelope calculation procedures.

It is shown that the maximum export values depend on the sets of limits represented in a significant manner. An analysis of a broader set of networks would be interesting to understand if the different limits become binding in a different order depending on the network design. In certain regions, LV networks have a very sparse grounding of the neutral, e.g. only at the substation. In this case, the inclusion of neutral-to-ground voltage limits may be crucial in determining the DOE. Finally, in the real world, DOE calculation should be done frequently and based on a state estimate, so that congestions are avoided with high likelihood while simultaneously avoiding unnecessary curtailment of PV. The tradeoffs between the frequency of the updates, accuracy of the estimates, and interactions between customers due to congestions are to be researched further.

Future work includes looking at different trade-offs between customer equity and export capacity.

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Analysis of power quality concerning COVID-19-related anomalies and integration of distributed energy resources

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***Abstract*—With the development of technologies and the decrease of prices, the number of end-users that decide to invest in distributed energy resources (DERs) continuously grows. Despite the improvement of financial and environmental aspects of the power system operation, a growing share of DERs can cause numerous technical challenges for distribution system operators (DSOs). Besides the integration of DERs, the novel COVID-19 disease created additional challenges for DSOs in 2020 and 2021. Due to a large number of single-phase loads and DERs, the increased consumption, the number of nonlinear loads, and power electronic devices in a distribution network, many challenges are related to power quality (PQ). In this paper, realistic case studies that consider anomalies caused by the COVID-19 pandemic and integration of DERs are presented. By using pandapower and its newly developed extension, different PQ indicators are calculated and the values of voltage magnitude, voltage unbalance factor (VUF), and total harmonic distortion (THD) are compared through different scenarios. In addition, the impact of a transformer's vector group on the PQ indicators' propagation through the observed distribution network is analyzed. In a conclusion, the optimal vector group, that successfully mitigates or at least decreases the values of PQ indicators and their propagation is proposed.**

***Index Terms*—COVID-19, distributed energy resources, distribution networks, power quality, transformer's vector group**

I. Introduction

In recent years, governments across the world have become aware of the power system's impact on the environment. As one of the leaders in the energy transition, the European Union (EU) has decided to increase the greenhouse gas emissions reduction, the share of renewable energy sources, and to increase energy efficiency. The targets defined in several deals and strategies [1], [2] have a common goal of the gradual transition towards an economy with net-zero greenhouse emission by 2050. In order to accomplish these goals, end-users connected to the low-voltage (LV) distribution network become more significant. They are encouraged to invest in low-carbon (LC) technologies through different governments' instruments, but also by the technological developments which have resulted in a significant decrease in prices of PVs and battery storage systems.

In power systems with a high share of LC technologies, distribution system operators (DSOs) must face the problems related to different aspects of power quality (PQ). The over-voltage problems caused by the integration of PVs, can be solved by the adjustment of the active and reactive power output of inverters [3]. The methodology proposed in [4] avoids the curtailment and calculates the maximum allowed amount of injected power to the grid at each time instant of the day and generates an active power management schedule for the prosumers.

Even though a significant number of end-users are three-phase connected to the LV network, their devices are connected to only one phase. Since the voltage unbalance causes network losses and the decrease in end-user devices performance [5], the voltage unbalance must be reduced and mitigated whenever possible. In smart grids, the reactive power capability of single-phase PV inverters can reduce voltage unbalance and energy losses in three-phase four-wired LV distribution networks [6].

Since most of the LC technologies are connected to the network through power electronics devices, PQ problems are often related to the higher-order voltage and current harmonics and the total harmonic distortion (THD). The authors in [7] developed a harmonic coupled model to calculate the harmonics generated by individual nonlinear home appliances, which is important since power-electronic devices adopted in home appliances inject harmonics in power systems. A probabilistic method that assesses both the impact of nonlinear loads in households and PVs on the harmonic distortion in the residential network is proposed in [8].

The rapid increase in the share of LC technologies in LV networks can result in reverse power flows that can reach

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the upstream MV network. The importance of multi-voltage analyses and the need for integrated MV-LV network modeling is demonstrated in [9]. The authors in [10] model a transformer admittance matrix for distribution network analyses, showing the importance of a vector group in different analyses. A propagation of PQ voltage and current unbalance for different vector groups is investigated in [11]. This paper presents an extended analysis of several PQ indicators and their correlation with a transformer's vector group. Moreover, the analyses include both integration of DERs and COVID-19 phenomena.

After identifying research gaps in the literature, the following contributions are proposed in this paper:

1) A comprehensive analysis of PQ parameters in a large-scale MV-LV distribution network is presented in this paper. Even though there are already papers that analyze several different PQ parameters [12], [13] using an open-source tool, they do not provide the analysis made for a large scale distribution network or the analyses are made on experimental networks [14], which often do not reflect the real-world scenarios.
2) The proposal of an optimal vector group of a transformer in the planning and operation of three-phase power systems. Based on the analyses of different PQ parameters in unbalanced power systems, a vector group of a transformer that contributes to a decrease in problems related to PQ will be proposed, so DSOs can mitigate problems and avoid further network reinforcement or the possible need for flexibility and additional expenses.

The rest of the paper is organized as follows: Methodology is presented in Section II. Case studies and scenarios are defined in Section III, while the results and the discussion about them are presented in Section IV. The conclusion are summarized in Section V.

II. Methodology

To understand the need for observing the impact of a transformer's vector group, the authors in several papers [15], [16] define a different set of equations that are valid for calculating an impedance of each vector group. The difference between vector groups is especially visible in models of the zero system sequence since the zero sequence current of higher-order harmonics is blocked when using specific vector groups. Those vector groups would be more suitable for avoiding the harmonics-related problems. However, the impact of vector groups on other PQ indicators is additionally investigated in this paper. Furthermore, the model of a transformer is correlated with anomalies caused by the COVID-19 pandemic and the rapid integration of DERs. All calculations and simulations are made using the pandapower tool and the extension for unbalanced harmonic analysis.

A. Voltage magnitude and unbalance

As a result of the unbalanced load flow analysis, phase voltages U_a, U_b, U_c of each node n in a network are calculated. To calculate VUF it is necessary to transform phase voltages into zero, negative and positive system voltages (1). After the voltages of each system are calculated, it is possible to calculate VUF$_n$ for each node using equation (2).

$$\begin{bmatrix} U_0 \\ U_1 \\ U_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} \quad where,\ a = 1\angle 120^\circ \tag{1}$$

$$VUF_n = \frac{U_{2,n}}{U_{1,n}} \cdot 100\% \tag{2}$$

B. Harmonic analysis

An unbalanced harmonic analysis is conducted with the tool developed as an extension of pandapower [17]. Using the tool, it is possible to run time-series simulations for different vector groups and to consider the characteristics of each group. In the first step, harmonic voltages are calculated for each higher-order frequency and all three phases of each node. From the values of phase harmonic voltages and the voltage magnitude of the fundamental harmonic, THDu, p, n values are calculated using equation 3.

$$THD_{u,p,n} = \sqrt{\sum_{h=2}^{H} \left(\frac{U_{p,n,h}}{U_{p,1}} \right)^2} \tag{3}$$

III. Case studies

Due to the difficulties and challenges created by the COVID-19 pandemic, three different scenarios (S), corresponding to the pre-lockdown (S1), hard lockdown (S2), and post-lockdown (S3) periods are created. Load data used in the simulations is collected from the smart meters installed at end-users nodes. Data were collected in three different periods, pre-lockdown, hard lockdown, and post-lockdown period. To additionally determine the impact of DERs penetration and a correlation with COVID-19 related anomalies, case studies (CS) in which some end-users have installed PVs and EVs are determined. Depending on the scenario, a certain share of end-users has installed single-phase PVs and EV charging stations. Nodes and phases to which PVs and charging stations are connected are randomly chosen in each defined case study and scenario. The first case is the referent case, without installed LC units (CS1), the second one is the case in which 40% of end-users have installed PVs and EV charging stations (CS2), and in the third, final case, 80% of end-users have LC technologies (CS3). Cases are determined as realistic ones since the EU expects to have the share of renewables of 40% in 2030 and 80% in 2050 [2], [18]. The harmonic current curves for end-users devices are created according to [19], [20], and for PVs according to [21]. The harmonic current curves for the EVs charging are created from the real-world measurements.

Simulations are made to determine voltage magnitude, voltage unbalance factor, and total harmonic distortion and to determine their correlation with a transformer's vector group. Three different vector groups were observed in simulations, Dyn5, Yyn0, and YNyn0 since for other vector groups the calculations do not converge at every time period even after

30000 iterations. Therefore they are omitted from the calculations and are not considered for usage in distribution networks planning and operation.

IV. Results and discussion

A. Voltage magnitude

Values of voltage magnitude are shown in Fig. 1. The boxplot graph shows the differences considering case studies and scenarios. A distribution of values in the case when there are no DERs installed is similar in all analyses. Phase voltages in LV networks do not violate the limitations and due to increased consumption during the hard lockdown period, voltage magnitude is generally lower in Scenario 2, no matter the vector group. The values are within the limitations both in an MV and LV part of the network.

In scenarios related to CS2, installation of DERs in 40% of nodes changes the conclusions drawn in the previous case, especially in an LV part of the network. The worst scenario is again S2, which represents the hard lockdown period, during which people spent the majority of a day at their households due to the government's restriction. Both lower (0.9 p.u.) and upper limitations (1.1 p.u.) are violated due to increased power caused by EV charging and excess PV production. The results show that the Yyn vector group should be avoided if only voltage magnitude is observed. However, the results show that other vector groups cannot mitigate the problems related to unallowed values of voltage magnitude. Also, the problems related to the limitation of the lower bound are larger than those related to the upper bound, since some values are below 0.8 p.u. which could cause serious problems in distribution networks. The voltage magnitude problems do not propagate to an MV network, no matter the vector group. Even though the range of values is higher than in CS1, especially when the YNyn vector group is observed, all values are between 0.96 and 1.03 p.u., and there are no outlier values that violate the defined limitations.

In CS3, the lowest values of voltage magnitude in a network are during the hard lockdown period, for the YNyn group. Even though the most of values are in the allowed interval, there is a significant number of outlier values that violate limitations defined for voltage magnitude in LV networks. The violation occurs during all scenarios, meaning that current strategies of planning and operation of distribution networks are not suitable for the passive integration of 80% of DERs. Moreover, the violations are serious, in some periods, the values are lower than 0.6 p.u., which could lead to more significant problems in the whole power system, despite the local characteristic of voltage problems. The propagation of voltage problems to an MV part of the network does not present serious issues, i.e., not even outlier values violate the limitation defined for MV networks. However, in the worst-case scenario, when the YNyn group is used during the post-lockdown period, the values come closer to the lower bound of the allowed voltage magnitude interval. Even though the analyzed LV network is well-dimensioned and there are currently no voltage problems, even with the increased consumption during the hard lockdown period, the results show the planned integration of DERs and further increase of the LC units share will cause voltage-related problems in LV networks. The values suggest that the problems caused by the integration of DERs could be serious and it could have a significant impact on future distribution networks. In spite of voltage magnitudes in LV networks, the problems are not transferred in an MV part of a network, and the values that violate the limitations do not occur. However, the trend shown in the simulations is concerning, and solutions that include end-users and DERs, e.g., flexibility, time-shifting of consumption, curtailment, Volt/Var control, etc., should be implemented in the planning and operation of future distribution networks.

B. Voltage unbalance factor

In most cases, end-users devices are single-phase connected to a network, which leads to voltage unbalance even in cases that describe the current situation, without a significant share of DERs. The dependence of VUF on the vector group and different scenarios is shown in Fig. 2. The results of CS1 in which end-users do not have installed LC units show that there is a certain amount of voltage unbalance. However, in all scenarios and for all vector groups, the value of VUF does not exceed 0.7%, the limitation defined in the Croatian distribution grid code [22]. Therefore, the problems related to increased voltage unbalance, e.g., network losses, are not so large without additional installed single-phase connected units. Similar to the analysis of voltage magnitude, this analysis shows that the voltage unbalance does not significantly propagate from one voltage level to another but is even lower in an MV part of the network. It is interesting to notice that the selection of a scenario does not play a significant role in the value of VUF. Unlike the analysis of voltage magnitude, in which the hard lockdown period led to increased consumption, and consequentially lower voltages, the difference between phase voltages cannot be correlated with the pre, hard, or post-lockdown scenario.

In CS2, 40% of nodes and connection phases of both PVs and EV charging stations are randomly determined. Compared to CS1, there is a significant increase of the VUF value, wherein all scenarios values violate the 0.7% limitation. Despite the violation, the majority of values are below the mentioned deviation, and only outlier values are higher than 0.7%. The cause of increased voltage unbalance is an uncoordinated installation of DERs and randomly chosen connection phases in all analyses. Therefore, it is hard to draw a general conclusion about the correlation between voltage unbalance and a transformer's vector group. The value of VUF could be decreased by determining an optimal connection phase, an installment of phase switching devices, PVs curtailment, smart charging of EVs, etc.

In the last defined case study, CS3, 80% of end-users are assumed to have installed PVs and to charge EVs at home charging stations. Same as in previous case studies, end-users with installed LC units are randomly chosen for each scenario and simulation for every vector group. Additionally,

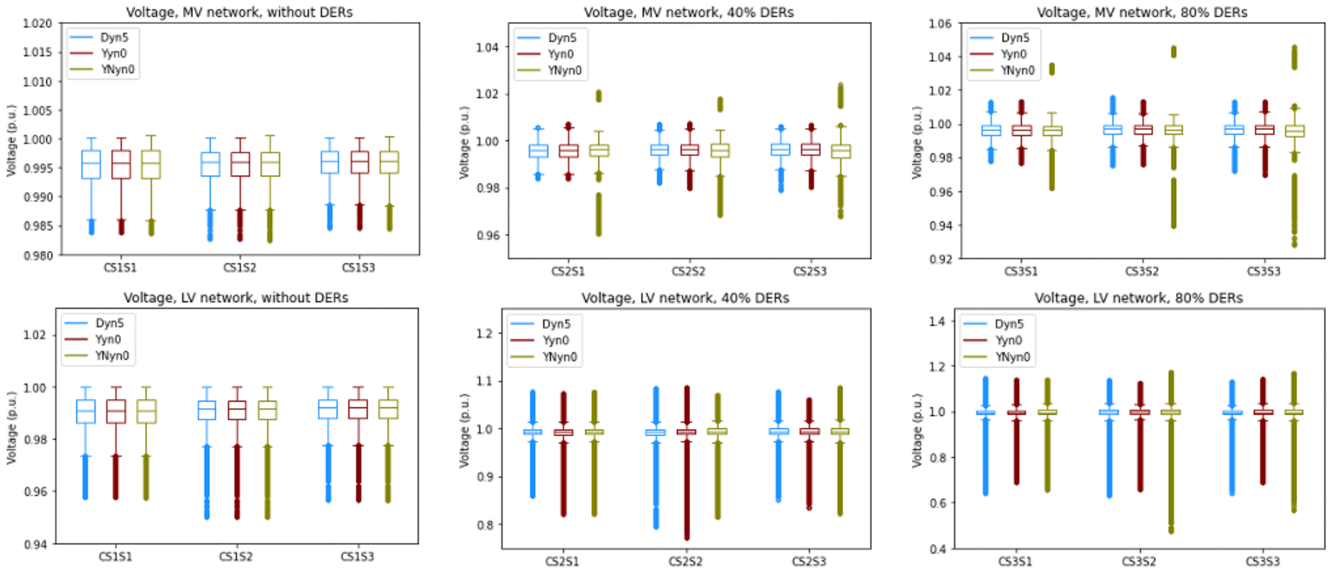

Fig. 1. Voltage magnitude(p.u.) - results

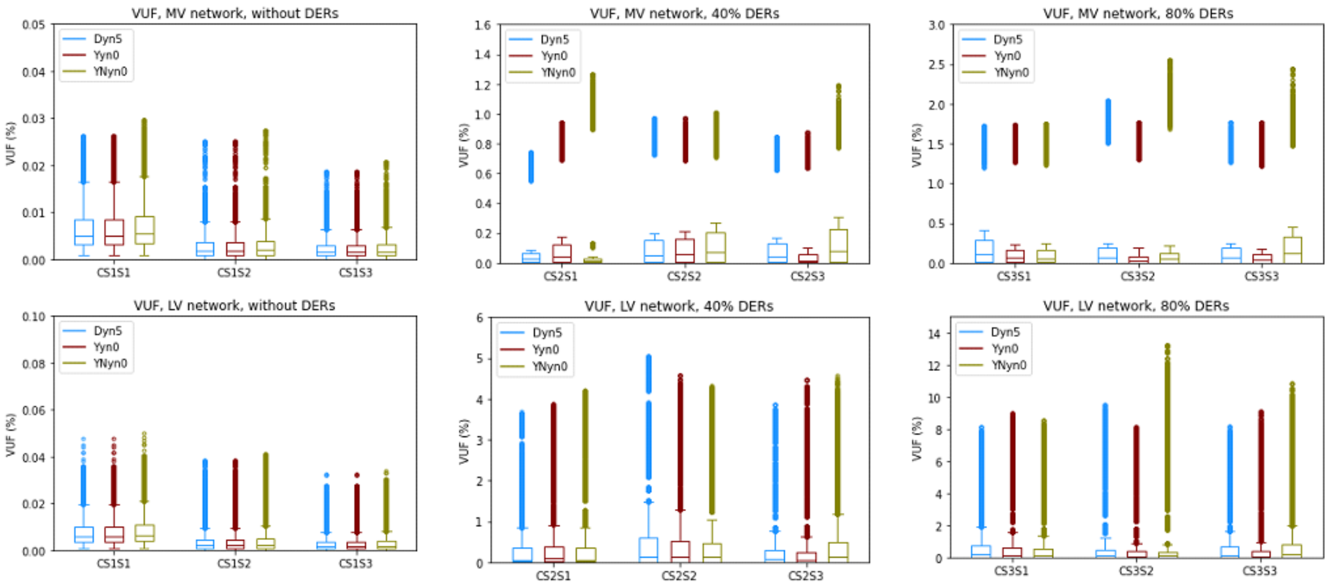

Fig. 2. VUF(%) - results

the connection phase is also randomly chosen. The results shown in Fig. 2 are not similar to the results of analyses made in CS1 and CS2. The values of VUF are significantly higher and besides the outlier values, even some values in the boxplot violate the defined limitations. Since the share of end-users with installed LC units is doubled, compared to CS2, the increase of VUF values was expected due to randomly selected connection phases, without any control of DERs integration. An increase of voltage unbalance this high leads to several problems in distribution systems planning and operation, including increased network losses, deterioration of equipment's performance, and shortening of equipment's life expectancy.

In the analysis of voltage unbalance that occurs with the integration of DERs at an LV level, a correlation between VUF, transformer's vector group, share of DERs, and the COVID-19 pandemic was investigated. Contrary to the analysis of voltage magnitude, the VUF values do not considerably depend on a vector group and the COVID-19-related scenario. The only significant correlation is to the share of DERs since the interval of VUF values increases with a larger number of uncoordinated and randomly installed single-phase LC units.

To avoid the problems caused by the voltage unbalance it is necessary to implement models and methods that will enable mitigation of voltage unbalance both via exploiting the potential of end-users or using physical devices such as power electronics or phase switching devices.

C. Total harmonic distortion

The same change as in cases of voltage magnitude and VUF happens in the analysis of total harmonic distortion (THD). Moreover, the dependence of the THD value was expected to be even more significant, due to specific characteristics of some vector groups, e.g., Dyn blocks the zero sequence current. Fig. 3 shows the results of the unbalanced harmonic analysis for different case studies and scenarios, defined in Section III. From the results related to CS1, it can be seen that both a vector group and the COVID-19-defined scenario have an important role in the change of THD value. The largest THD values occur during the hard lockdown period and it happens during enlarged consumption. Enlarged consumption led to the increased current at the fundamental frequency. Since higher-order frequency currents are calculated from the defined harmonic current spectrum and the value of the fundamental frequency current, harmonic currents at a higher frequency are also larger than in other scenarios. Due to the previous-mentioned blocking of zero sequence currents, the values of VUF are lowest when a network is modeled with the Dyn5 vector group of transformers. Due to a difference in the impedance calculations, YNyn causes larger harmonic pollution than the Yyn vector group. A similar situation is with the propagation of harmonics to an MV part of the network, where the values follow the trend of those in an LV network but are significantly smaller. Both in an LV and an MV part of the network, the values do not violate the limitation defined in the standards [23], [24].

In CS2, 40% of end-users have installed DERs. Since both EV charging stations and PVs are connected with power electronic devices, which are relevant harmonic polluters, the value of THD is much more significant compared to CS1. The trend remains the same as in the previous case, and both scenario and vector group have a significant impact on THD. As it can be seen in Fig. 3, using the Dyn5 vector group in scenarios when COVID-19 restrictions are not so strict can prevent the occurrence of violating limitations. In spite of the fact that several values threshold the limitations even in the best-case scenario, all values in the boxplot and the majority of outlier values are lower than the 8% value. Since the values must be lower than the limitation in 95% of ten-minute intervals during one week, using the Dyn5 vector group ensures the integration of DERs in an LV network. Even if the resulting harmonic pollution negatively affects a network and causes unwanted problems in the planning and operation segments, those problems could be mitigated with small or no investment. The propagation of harmonic distortion to an MV network exists but the values of THD do not present the potential problem for a DSO.

As it can be seen in Fig. 3, the harmonics-related problems in CS3, when 80% of end-users are equipped with LC units, are the largest and can cause serious problems in a distribution network. Similar to CS1 and CS2, the largest THD is during the hard lockdown period and YNyn vector group but even in the best case, the values of THD importantly violate the defined limitations. Not even using the Dyn5 vector group can help in avoiding harmonic pollution with the high share of DERs. Since only the outlier values violate the limitations, smart charging of EVs, PV curtailment, or installation of active and passive filters could potentially reduce harmonic pollution and simultaneously enable penetration of DERs and accomplishing the goals related to the increase of RESs share and the reduction of greenhouse gas emissions. Observing an MV part of the networks leads to the same conclusions as in CS1, and CS2, integration of DERs in an LV network does not significantly contribute to the harmonic distortion in an MV network, especially in the case of using the Dyn vector group. If the integration continues and the share of DERs in an MV network continues to grow as rapidly as it currently grows, the propagation should be prevented, both by exploiting the end-users potential and by installing physical devices that are able to reduce harmonic distortion.

Even though the share of harmonic polluters constantly grows, the results of the harmonic analysis show that if using the Dyn5 vector group, a distribution network can withstand an integration of DERs to some level. Since decarbonization is an inevitable process, the share of DERs will continue to increase both in MV and LV distribution networks. Same as voltage magnitude and unbalance, harmonic distortion could lead to unwanted problems in the planning and operation of distribution networks. Therefore, it is important to encourage end-users to become more flexible and to install additional devices which will reduce harmonic distortion.

V. Conclusions

To investigate the preparedness of the current distribution network for the integration of DERs and the COVID-19 pandemic, a real-world distribution network was created. The results show that the problems in distribution networks without DERs (CS1) do not exist, i.e., the values of all observed PQ indicators do not violate defined limitations, both in an MV and LV part of the real-world network. In the second case study (CS2), 40% of end-users have installed PVs and charge EVs at home charging stations. As expected, the values of all PQ indicators are worse than in CS1 but the limitations are violated in a few time periods. In the last case study (CS3), the values of calculated PQ indicators show that the violation of boundaries is inevitable with the passive integration of DERs since the violation is larger and it happens more often than in previous cases.

Additionally, the correlation between PQ indicators and a transformer's vector group was investigated. The largest dependence to a vector group was recognized in unbalanced harmonic analysis, since using the Dyn vector group significantly reduces THD. Voltage magnitude also depends on the vector group due to differences in the impedance of each group and correlation with VUF is not so significant due to a larger dependence on the distribution of consumption among phases.

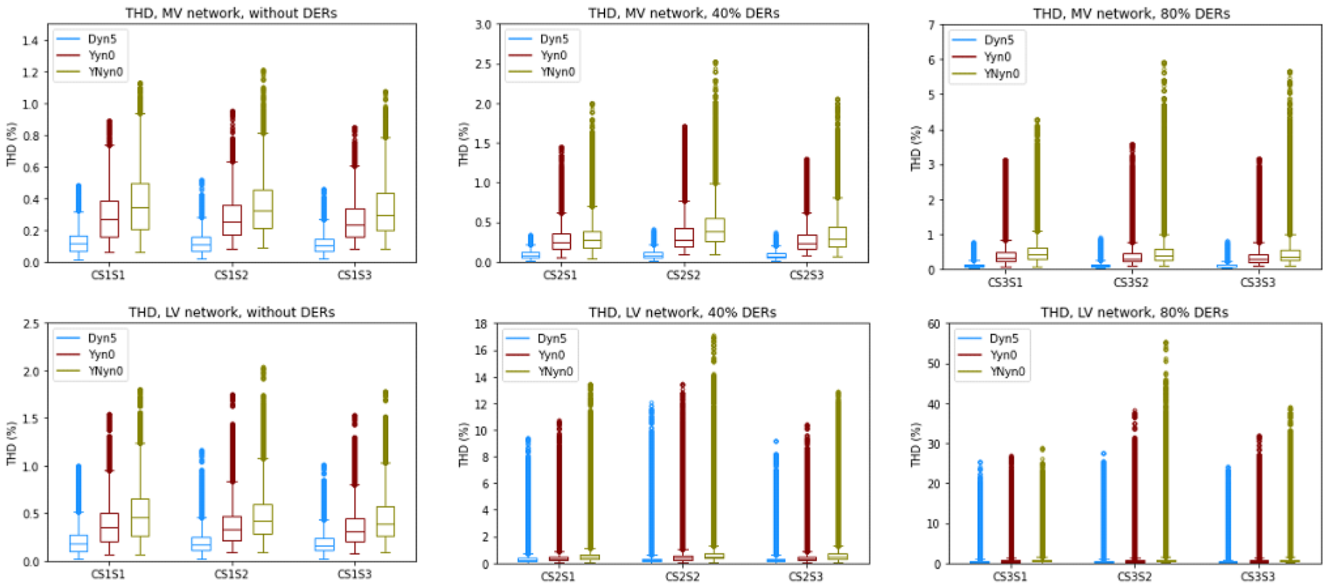

Fig. 3. THD(%) - results

The results also show that using the optimal vector group is not enough for the mitigation of PQ-related problems and other potential solutions, e.g., an installation of physical devices and exploitation of physical devices will be investigated in future analyses.

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GIS visualization of COVID-19 impact on PQ indicators in distribution networks: A case study of Croatia

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ABSTRACT

A large part of 2020 and 2021 was marked by the COVID-19 pandemic. A global pandemic has caused changes in people's behavior and has created challenges for multiple industries and numerous sectors. One of the most affected sectors is the electricity sector, which already deals with challenges caused by decarbonization and the integration of low-carbon technologies. Newly caused challenges are especially important for Distribution System Operators (DSOs) since they are responsible for the planning and operation of distribution networks and for resolving the problems caused by the change of end-users' habits. To identify and visualize pandemic-induced changes, an integrated geographic information system (GIS)-based tool is developed and presented in this paper. After identifying errors in GIS and end-users' consumption data and preprocessing them, pandapower and the developed harmonic calculation extension are used for the analysis of different power quality (PQ) indicators in low-voltage (LV) distribution networks. As a final step of the developed tool, the impact of COVID-19 on PQ indicators is visualized using GIS.

Keywords: COVID-19, end-users, geographic information systems, low-voltage network, power quality

1. INTRODUCTION

The end of 2019 was marked by the appearance of the new coronavirus disease (COVID-19). The novel disease changed the world as we know it and has caused the slowing and closing of the economy, industry, tourism, electricity, and many other business sectors. Several research papers consider the impact of COVID-19 on different aspects of power system planning and operation, e.g., electricity markets and market operations [1], CO_2 emissions [2], consumption of end-users [3], etc. Based on the measurements collected from the smart meters, the impact of COVID-19 on voltage magnitude, voltage unbalance, and total harmonic distortion (THD) is shown in this paper.

The challenges caused by the COVID-19 pandemic, and other changes in the distribution networks, e.g., an integration of distributed energy resources have put the focus on the need for the development of tools that can be used in the planning and operation of distribution networks. The fundamental idea behind these tools is based on the communication between different systems and databases which need to be integrated so that Distribution System Operators can use them in different network analyses.

One of the systems that is recognized as an important part of distribution networks operation is the Geographic Information System (GIS). Often, using GIS data is not possible without further processing and editing, needed to correct identified errors [4]. Since GIS is one of the many systems and tools used in the planning and operation processes, it is important to enable communication between different systems, databases, and tools [5].

Changes caused by the penetration of distributed energy resources (DERs) can cause several problems related to power quality (PQ). A high number of single-phase connected devices can lead to an unallowed voltage unbalance [6], which consequently causes increased technical losses in distribution systems [7]. DERs and home appliances are power electronic (PE)

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devices-interfaced, which impacts harmonic distortion in distribution networks. Therefore it is important to develop analyses tools, evaluate and potentially mitigate the increased distortion [8]. Some of the PQ-related problems, such as overvoltage or undervoltage can be mitigated by a joint operation of multiple DERs, e.g., PVs and EVs [9], [10]. In this paper, PQ parameters are analyzed by using pandapower [11] and a newly developed balanced and unbalanced harmonic analysis tool [12] developed by the authors of this paper.

Based on the literature review and identified research gaps, we propose the following contributions in this paper:

- Development of an open-source, highly automatized, GIS-based tool, that is used in the first step for editing and processing the data and removing the detected errors.
- A comprehensive analysis of PQ indicators in LV network. Analyses are made with data from before and during the COVID-19 pandemic. Therefore, the impact of COVID-19 on an LV network and anomalies caused by the pandemic are presented in this paper.
- After the simulations, the results are visualized using a GIS-based tool. The visualization of PQ indicators contributes to an easier assessment of the correlation between COVID-19 related anomalies and PQ indicators in LV residential networks.

2. METHODOLOGY

2.1 GIS data and the mathematical model of a network

Even though there are numerous advantages of GIS data, as mentioned before, often it cannot be used in the initial form. Also, not all data about distribution networks, e.g., end-users' consumption, is stored in one system or database. Therefore, it is necessary to develop an integrated tool with enabled communication between several systems and databases, that has the possibility of removing errors and prepare data for further analyses.

The tool presented in this paper is based on open-source technologies, and with combining features of QGIS, Python programming language, and PostgreSQL with the PostGIS extension, edits data and removes errors from an initial set of Croatian DSO's GIS data. The first step is the detection of errors and afterward, the developed integrated tool is used for further processing of data. Several errors in GIS data were detected:

- Continuity of a polyline
- Unknown beginning and end node of an LV cable/line
- Disconnection of an LV cable/line and an MV/LV substation or an LV switch cabinet
- Unknown technical attributes of an LV cable/line
- LV cable/line without known end node
- Redundance of point objects

After the detection of all errors, using the automatized process, the developed tool successfully removes all errors and prepares the data for further analyses. The flow chart that represents an integrated tool and represents all the steps is shown in Fig. 1.

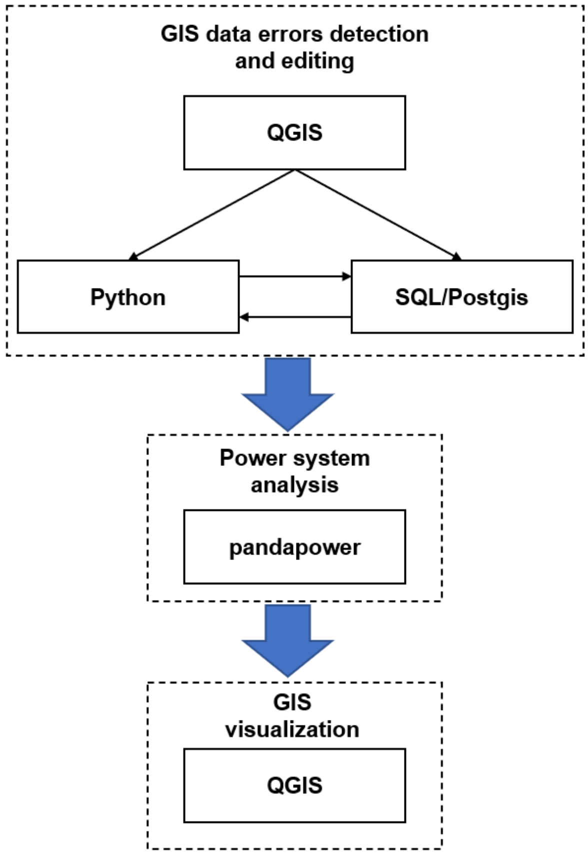

Fig. 1 Flow chart of the integrated tool

2.2 PQ analysis

In the first step of the PQ analysis, the open source, Python-based, pandapower library is used for the unbalanced load flow calculations. As a result of a calculation, phase voltage magnitudes and angles are calculated for each node. Based on the phase voltages and relation between phase and zero, negative, and positive sequence systems, voltage unbalance is calculated for each node in the observed network. As an upgrade of the pandapower library, a harmonic analysis tool is developed combining some of the already integrated functionalities and additions that allow full implementation of mathematical model briefly described with the following equations.

After the impedance matrix is calculated for a fundamental harmonic using already integrated pandapower functionalities, the phase impedance matrix $[Z_{abc,h}]$ for each higher-order harmonic h is calculated for a network consisting of elements that connect nodes k, l and that are impacted by non-fundamental frequencies defined with equation (1).

$$Z_{h,k,l} = R_{1,k,l} + jhX_{1,k,l} \quad (1)$$

As an input in the unbalanced harmonics calculation a harmonic current spectrum, determined as a percentage of fundamental harmonic current is defined for each load connected to a certain phase of a node. From the calculated harmonic impedance matrix and harmonic currents, a harmonic voltage drop vector is calculated with the equation (2).

$$[\Delta U_{abc,h}] = [Z_{abc,h}] \cdot [I_{abc,h}] \quad (2)$$

Since the voltage drop calculated with (2) is defined as a difference between the referent and all other nodes, it is necessary to calculate the voltage of the referent node. Same as for the calculation of the voltage drop, to calculate the voltage of the referent node, a phase impedance matrix of the referent node, i.e., of the external grid connected to the referent node, and a current that is being injected in the referent node must be determined. From the voltage of the referent node and the voltage drop vector, the voltage of each node in the observed network is calculated. The described procedure is conducted for each higher-order harmonic.

After the values of the harmonic voltages are determined for every higher-order frequency, it is possible to determine THD_n for every node n in the observed network (3).

$$THD_n = \sqrt{\sum_{h=2}^{H} \left(\frac{U_{n,h}}{U_1}\right)^2} \quad (3)$$

2.3 GIS visualization

After running simulations, the results obtained by pandapower are stored in a database. To analyze the impact of COVID-19 on LV networks, the QGIS tool was used to visualize the results of simulations. An analyzed network was visualized, where nodes are presented with various styles. Each of the styles can be matched with a value of an observed PQ indicator.

3. CASE STUDIES

An LV feeder used for an analysis in this paper is a real-world feeder with 66 nodes, 43 three-phase and single-phase connected users, and 64 lines.

Based on the government's regulations and considerations, two different time periods relevant to COVID-19 impact were defined. Both time periods are defined with real-world measurements of consumption, from which active and reactive power are calculated. The first period is defined as a pre-lockdown period, a period at the beginning of 2020, when there was no serious effect of COVID-19 and there were no restrictions. Second period is defined during a hard-lockdown period, when numerous sectors were closed, business was stopped, and most people spent the majority of their day at home.

Based on consumption measurements collected at 30-minute time intervals during two-week period, unbalanced load flow and harmonic calculation were made, and results of the simulations were used for comparison. The comparison was made using equation (4):

$$\frac{PQ_{ind\,hard} - PQ_{ind\,pre}}{PQ_{ind\,pre}} \cdot 100\% \quad (4)$$

where $PQ_{ind\,hard/pre}$ represents the value of the calculated PQ indicator (voltage magnitude, VUF, THD) both before and during the pandemic. The comparison was made using the average value calculated for each node, from values of PQ indicators for each period. After the values are compared, it is possible to determine how significant was a change of the value of a certain PQ indicator. After determining the impact of COVID-19 on PQ indicators in a residential distribution feeder, a GIS-based tool is used for visualization of the comparison.

4. RESULTS

A GIS visualization of the voltage magnitude change during the hard-lockdown is presented in Fig. 2. The results show that, compared to a pre-lockdown period, voltage magnitudes have decreased. However, the results show that the voltage magnitude in the lockdown period was not significantly lower compared to the pre-lockdown period. This can be explained by a fact that a hard-lockdown period came in the spring months when the consumption is generally lower than during the winter months, which is the pre-lockdown period. The differences would be more significant during the post-lockdown period that occurred during the summer months when a high number of HVAC devices used for cooling would lead to the increased voltage drop. Both before and during the lockdown, there are several periods in which voltage magnitude is lower than the limitation defined in European standards and national grid codes.

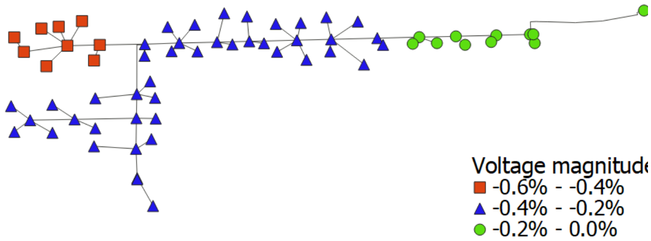

Fig. 2 Voltage change during hard-lockdown

The change of voltage unbalance factor in the lockdown period is visualized with Fig. 3.

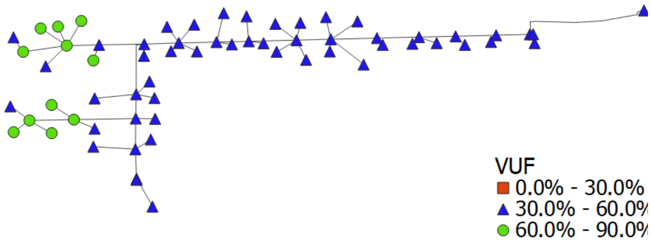

Fig. 3 VUF change during hard-lockdown

Unlike the voltage magnitudes, which decreased during the lockdown, VUF increased by more than 30%, and even for more than 60% at some nodes. The increase happened due to the increase in phase consumption that led to larger deviation between phase voltages. Such increase of voltage unbalance was expected only with the integration of single-phase connected DERs, especially when the connection phase is unknown [6]. The similar phenomena created only by the change of the end-users' behavior showed that the traditional planning and operation of distribution networks are not reliable during unexpected events. Also, the COVID-19 phenomena emphasize the need for the development of new tools and an approach in the planning of new, active distribution networks. Despite the increase, both in the pre-lockdown and hard-lockdown period, VUF values do not violate the limitations defined in European standards and national grid codes.

The impact of COVID-19 on the value of THD is shown in Fig. 4. With the exception of one node, the value of THD has increased in all other nodes during the hard-lockdown period. Similar to the case of analyzing voltage magnitudes, the change of the THD value is not so significant. The reason is that the characteristic of loads that are more used during winter are nonlinear and their contribution to the harmonic pollution is more significant. The increase is not as emphasized as in the case when VUF was observed, but it shows that further increase of power electronics' share can lead to potential problems related to harmonic distortion. Also, in some observed periods, COVID-19 restrictions caused a violation of limitations defined for THD.

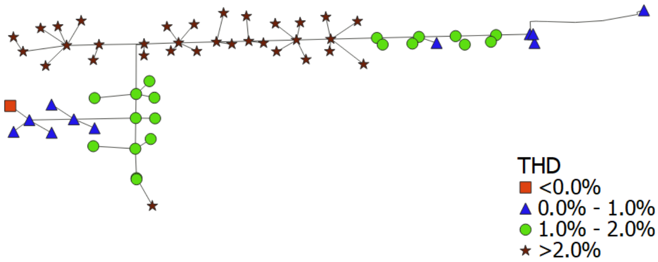

Fig. 4 THD change during hard-lockdown

5. CONCLUSION

In this paper, the impact of COVID-19 on PQ indicators in an LV residential feeder is being analyzed with an integrated tool based on the GIS technology and the open-source pandapower library. The tool is used for detection and removing errors in the initial GIS data set, unbalanced load flow and harmonic calculations, i.e., determining PQ indicators in an LV network, and a visualization of PQ indicators changes during the lockdown period.

The results show that the lockdown negatively affected all observed PQ indicators, i.e., voltage magnitude decreased, while VUF and THD increased. Even though the changes do not cause a significant problem in the operation of distribution networks, it shows the concerning trend of PQ distortion, which can be more emphasized with the uncontrolled installation of DERs. Due to increased consumption and a longer stay at home during the pandemic, it would be possible to exploit the end-users' potential and with different approaches, e.g., demand-side management or flexibility, solve PQ-related problems in LV networks.

Since after the first hard-lockdown period, there were several different periods in which there were no or few restrictions, e.g., a period of soft-lockdown, it would be beneficial to observe how the change of regulations affects different technical parameters in LV distribution networks. With the tool presented in this paper, it is possible to make analyses for other periods and also for other case studies, and not only for those defined by the COVID-19.

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Biography

Tomislav Antić was born in Zagreb in 1995. In 2014, he finished XV. gymnasium, and at the University of Zagreb, Faculty of Electrical Engineering and Computing, he completed his bachelor's and master's studies in 2017 and 2019. After completing his master's studies, he started employment as an assistant at the Department of Energy and Power Systems at the Faculty of Electrical Engineering and Computing, and in 2020, he enrolled in doctoral studies at the same faculty.

As an assistant, he participated in the teaching of bachelor and master courses, including Databases, Electrical Energy Distribution Systems (Distribution Networks and Distributed Generation), Geoinformation Systems, Power Quality, etc. He also participated in preparing several bachelor's and master's theses.

In addition to his teaching activities, Tomislav actively participates in projects related to distribution networks' planning and operation and in the preparation of technical studies.

During his doctoral studies, he spent six months as a visiting researcher at University College Dublin and eight months as an intern at the International Renewable Energy Agency.

He is the author of more than 15 papers published in journals and conference proceedings, and he is a reviewer in several A-category journals.

The field of research includes the development of methods and tools for simulations and analysis of distribution networks, optimisation and modelling of distribution networks, application of geographic information systems in the power systems, power quality, but also other areas related to planning and operation of distribution networks with a high share of distributed energy resources.

He is a member of scientific and professional associations IEEE, IEEE PES and HO CIGRE.

A detailed list of published work is available at:

- `https://orcid.org/0000-0002-4183-0735`
- `https://scholar.google.com/citations?user=aEc5oP4AAAAJ&hl=en`
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Životopis

Tomislav Antić rođen je u Zagrebu 1995. godine. 2014. godine je završio XV. gimnaziju, a na Sveučilištu u Zagrebu Fakultetu elektrotehnike i računarstva završio je preddiplomski i diplomski studij 2017. i 2019. godine. Po završetku diplomskog studija zapošljava se kao asistent na Zavodu za visoki napon i energetiku Fakulteta elektrotehnike i računarstva, a 2020. godine upisuje doktorski studij na istom fakultetu.

Kao asistent sudjelovao je u izvođenju nastave na predmetima preddiplomskog i diplomskog studija uključujući Baze podataka, Elektroenergetski distribucijski sustavi (Razdjelne mreže i distribuirana proizvodnja), Geoinformacijski sustavi, Kvaliteta električne energije, itd. Također, sudjelovao je u izradi nekoliko završnih i diplomskih radova na preddiplomskom, odnosno diplomskom studiju.

Osim aktivnosti u nastavi, Tomislav aktivno sudjeluje na provođenju projekata iz područja planiranja i vođenja distribucijskih mreža te u izradi stručnih studija.

Tijekom doktorskog studija proveo je šest mjeseci kao gostujući istraživač na University College Dublin te osam mjeseci kao pripravnik u International Renewable Energy Agency.

Autor je više od 15 radova objavljenih u časopisima i u zbornicima skupova, a recenzent je u nekoliko časopisa A kategorije.

Područje istraživanja obuhvaća razvoj metoda i alata za proračune i analize distribucijskih mreža, optimizaciju i modeliranje distribucijskih mreža, primjenu geografskih informacijskih sustava u elektroenergetici, kvalitetu električne energije, ali i ostala područja vezana uz planiranje i vođenje distribucijskih mreža s visokim udjelom distribuiranih izvora energije.

Član je znanstvenih i stručnih udruga IEEE, IEEE PES i HO CIGRE.

Detaljnom popisu radova moguće je pristupiti:

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