Impact of End-Users on Financial, Environmental and Technical Aspects in Low-Carbon Technology-Rich Low Voltage Networks

Tomislav Antić,
University of Zagreb Faculty of Electrical Engineering and Computing,
Zagreb, Croatia
tomislav.antic@fer.hr

Abstract — **With the development of technologies and the decrease in prices, the number of end-users that decide to invest in low-carbon (LC) technologies continuously grows. End-users are encouraged through incentives and other financial benefits to install photovoltaics (PVs), battery storages, or to drive electric vehicles (EVs). Since the goal of the European Union (EU) and other governments is to decrease greenhouse gas emissions in the following years, the role of end-users in the energy transition is becoming more important. Besides financial and environmental aspects it is important to observe technical aspects in power systems with a high share of LC technologies. High penetration of LC technologies can cause different problems related to power quality (PQ). Therefore, it is important to analyze the impact of LC technologies on the PQ parameters, determine in which cases the limitations are violated, and propose methods that will enable distribution system operators easier planning and operation of the distribution network with a high share of LC technologies. This paper presents a review of such methods, but also gives a brief introduction into the development of the planning and the operation of distribution systems, with a focus on the importance of the modeling and analyses in the low-voltage (LV) distribution network. Since the end-users are becoming more important participants in the energy transition, their impact on the network is presented in the paper.**

Index Terms — **low-carbon technologies; geographical information systems; distribution networks; power quality; flexibility; local energy markets;**

I. 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 2030 Climate Target Plan [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 the 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 over the 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 [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 technological development but also by market conditions and increasing electricity prices. The share of battery storage systems follows the growth of the share of renewables. According to [5], it appears that the capacity of battery storage systems will triple by 2030 if the share of renewables doubles. Similar to the solar modules price, the price of residential battery storage has decreased through the years and it is expected to continue decreasing in the 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 influential on the price, the decreasing price of batteries should result in lower prices of EVs through the years. With the decrease of prices and financial relief 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 the EU and other governments.

The rest of the paper is organized as follows: Section II briefly introduces the modeling and calculation methods in the LV network and the importance of end-users' flexibility. Section III gives a detailed description of LC technologies' impact on the LV network and presents the results of LC technologies' impact on the voltage unbalance in real-world Croatian LV network. Finally, Section IV highlights the conclusions and future work.

II. Planning and Operation of Distribution Networks

With the development of technology, the traditional structure of power systems is being abandoned and MV and LV networks are becoming more important, not only in terms of distribution and consumption but also in terms of the production of energy. The high penetration of RESs shifts the production from the transmission to the distribution network. Even though some of the RESs, e.g., wind powerplants are connected to the transmission network, a large number of the RESs are connected to the distribution network, both MV and LV network.

Methods developed and analyses made in the high voltage (HV) network cannot be adopted in the MV and especially in the LV network. A radial configuration, a higher R/X ratio, a high number of RESs, a three-phase configuration, intermittent production, etc. are the reasons for the necessity of new techniques and methods that will be used for analyses in the distribution network.

A. GIS Tools in Power System Analyses

Geographical Information System (GIS) has an important role in the development of new methods and tools that are used both in the MV and LV network. GIS data are becoming more important and are often used in distribution network modeling [6] and distribution network analyses, e.g., distribution networks with a high penetration of PVs [7] and future distribution networks [8]. The Croatian Distribution System Operator's (DSO's) GIS tool is used for the distribution network planning with the help of heuristic and genetic algorithms [9] and the open-source Open Street Map GIS tool is used for the distribution network planning in [10]. Authors in [11] analyze the voltage conditions, the network losses, and the difference between a radial and meshed MV network. All the analyses are made in the synthetic distribution network with high renewables penetration, which is created with the help of GIS tools. Authors in [12] propose a GIS integrated automation of a near real-time power flow (PF) service for networks with the high share of a local generation and new options of retail and wholesale of electricity. GIS integrated automation has given rise to the opportunity for new PF management mechanisms for prosumers.

B. New Method for Planning of Distribution Networks

Since the rapid growth of the share of LC technologies, there is a necessity for a number of algorithms that will enable the planning and operation of smart distribution networks, especially LV networks. Authors in [13] propose a practical and scalable, stochastic, progressive multi-year planning methodology that considers technical, customer economic, and environmental aspects to make holistic planning decisions for existing LV networks to accommodate EVs in coming years. The approach is implementable by DSOs as it builds on existing power flow analysis tools, which are not affected by network size.

The aim of the planning approach proposed in [14] is to increase the decentralized installed PV power as well as the decentralized produced energy while accepting small active power curtailments. This goal is only achievable if the DSO can curtail active power in a feeder or switch off PV installations for seldom periods when the voltage upper limit is reached. [15] presents a planning method of PV-ESS system in distribution networks. To improve the rationality of traditional configuration schemes, the proposed model considers PV penetration. Consequently, an actual distribution network is studied to verify the effectiveness of the planning method. In order to address the positive ecological effects of sustainable energy, a PV penetration term reflecting the cushioning role of distributed PV in lessening pollution is added to the objective function. Numerical calculation results guarantee the effectiveness and rationality of the proposed configuration strategy. Due to the consideration of PV penetration, the planning scheme is more appropriate in current energy development trends, which encourage the large-scale application of distributed sustainable energy.

Given the limitations of traditional load forecasting in active distribution network planning (ADN), [16] establishes a trusted output model of intermittent DG such as WG and PV, which makes the load forecasting result more scientific and reasonable. Based on load forecasting, a bi-level optimization model of ADN planning is constructed to achieve the grid planning and energy storage system location and capacity. Finally, an economic park is taken as an example to verify the load forecasting and bi-level optimization methods. The calculation results show that the proposed method has a certain practical application value.

C. Power Flow Methods for Unbalanced Distribution Networks

Since the configuration of the LV network is different compared to the MV and HV network, the traditional operation methods cannot be adopted. PF methods such as Gauss-Seidel or Newton-Raphson must be improved or replaced with newly developed methods to analyze LV networks. Newton PF method described in [17] extends the Newton PF method for single-phase problems to three-phase PF problems. The mathematical model of the load, three-phase load connection, and three-phase transformer connection are studied and applied in the numerical experiments. The authors introduced six possible versions of the Newton PF method for three-phase power systems, and the extended polar current mismatch (NR-c-pol) and the Cartesian current mismatch (NR-c-car) versions are explained in detail.

A study [18] presents the modeling of distribution network elements and their implementation in the backward/forward sweep (BFS) PF method. An already existing BFS method is improved by using the breadth-first search method for network renumbering and the creation of a modified incidence matrix. The proposed method is used for the calculation of power losses in the unbalanced and symmetrical networks which are compared. The results show that although the three-phase calculation model is more complex than the symmetrical model, and thus it lasts longer, an improvement presented by the authors makes the proposed method suitable for application in real-time analyses. Since the BFS method is the most commonly used PF method in the LV distribution network, authors

in [19] also analyze the LV network using the BFS method. Authors modify the already developed method without ignoring the effect of the neutral conductor through Kron's reduction method. The majority of loads in LV distribution networks are single-phase connected and are supplied through a phase conductor and the neutral. Results of the paper show that the proposed method achieves significantly more accurate results than relevant existing methods with a slight increase in the required iterations due to the increased complexity.

In practice, the LV side of the distribution transformer is often asymmetric. Due to the lack of information, the existing PF methods in LV distribution networks assume that the voltage phase angle of the slack bus is symmetric. Based on the actual smart meter measurements, taking phase A of the slack bus as a zero-phase reference point, the PV and PQ model of phase B, and phase C for the slack bus are constructed. Considering the actual access mode and control mode of the photovoltaic inverter power in the LV distribution network, a more realistic power and voltage-independent control model of the three-phase relative to the neutral point is established. Based on the above two constructed models, authors in [20] propose a three-phase power flow model of a low-voltage distribution network considering phase asymmetry and photovoltaic access. Results of the simulation show that the constructed model can effectively and accurately calculate the three-phase PF in the LV distribution network with the phase asymmetry and PV access.

With the high penetration of the LC technologies with the unpredictable and intermittent production and consumptions, especially PVs, in the LV network, there is a necessity for the development of tools that are able to calculate voltages and currents in power systems with the production's and consumption's uncertainty. Authors in [21] present a review of probabilistic load flow approaches for power distribution systems with PV generation and EV charging. Authors present modeling the uncertainty of PVs, EVs, and the correlation between them. Also, the authors present the probabilistic PF method and emphasize the potential for improvement and for playing a vital role in future distribution systems.

After the development of PF methods and with the distribution network transition from passive to active, a number of optimal power flow methods (OPF) was introduced. [22] presents a three-phase AC OPF scheme that helps the system operator in PV-rich distribution networks. Authors in [23] propose a novel non-linear programming (NLP) approximation for OPF problems that include shiftable loads and complements it with a multi-version heuristic technique to efficiently handle large-scale mixed-integer NLP OPF problems with the high presence of shiftable loads. Alternative approaches proposed in the paper are shown to be scalable, providing fast and accurate solutions in the high number of examined cases. Even though the proposed ranking scheme is simple, it presents consistent results regarding the performance of each approach for different problem sizes. [24] presents a novel, generic, and versatile OPF framework including various residential flexibility resources. Since the attention has been paid to the modeling aspects, authors proposed a cost-modeling based on customer-driven flexibility, customer-driven modeling, such as PVs, shiftable loads, flexible loads, EVs, energy storages, etc. The developed model aims at achieving cost-optimal operation by considering practical issues such as limited flexibility resources controllability or minimizing 'disruptions' of the customer-desired operation of each device. A model developed in [25] presents an extensive multi-period OPF framework for smart LV distribution systems that rely on residential flexibility for combating operational issues. The proposed unbalanced OPF serves two key functions: it proposes and compares the performance of state-of-the-art device models for unlocking the flexibility potential of smart distribution networks and it provides up-to-date guidelines concerning how each of the most commonly employed (or ignored) modeling choices affect the quality and the reliability of the solution.

D. Unbalanced Network Modelling

In practice, most distribution systems are operated in unbalanced conditions. In order to use a three-phase PF, network elements must be modeled in a way that enables using the developed algorithms. Most of the algorithms reduce the three-phase four-wire LV distribution network to a three-wire model [26]–[29]. The network is reduced by using Kron's reduction. Since the assumptions in Kron's reduction is that the neutral wire is multi-grounded and that the neutral voltage at every grounded point. This assumption is acceptable in systems with the grounded neutral, including the Croatian distribution system.

Authors in [30] describe the conventional impedance modeling and the impedance modeling that include impact of neutral voltage. Fig. 1 presents a grounded model of the distribution network which is used in Kron's reduction method.
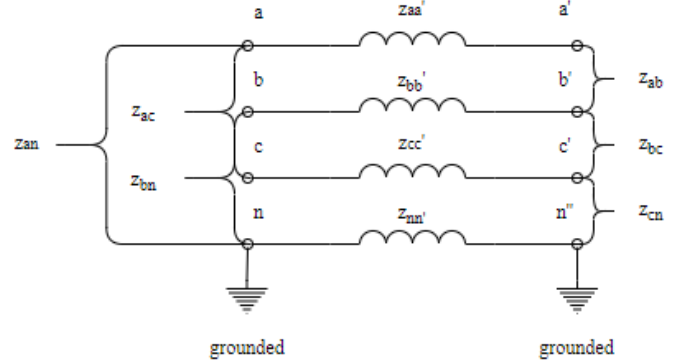

Fig. 1 Grounded neutral model of distribution network

Self-impedance (1) and mutual impedance (2) of each conductor are defined in [31], [32]. Since the practice in Croatian distribution networks is to define impedance in Ω/km, (3) and (4) present self-impedance and mutual impedance of each conductor which are calculated according to [18].

$$z_{ii} = R_i + 0.0953 + j0.012134 \cdot \left[ln\left(\frac{1}{GMR_i}\right) + 7.934 \right] \Omega/mi \quad (1)$$

$$z_{ij} = 0.0953 + j0.012134 \cdot \left[ln\left(\frac{1}{D_{ij}}\right) + 7.934 \right] \Omega/mi \quad (2)$$

$$z_{ii} = R_i + 0.05 + j0.0628 \cdot ln\left(\frac{93\sqrt{\rho}}{GMR_i}\right) \Omega/km \quad (3)$$

$$z_{ii} = 0.05 + j0.0628 \cdot ln\left(\frac{93\sqrt{\rho}}{GMR_i}\right) \, \Omega/km \qquad (4)$$

Equations (1) and (2) or (3) and (4) are used to calculate the primitive impedance matrix of a node Z_{prim} (5).

$$[Z_{prim}] = \begin{bmatrix} z_{aa'} & z_{ab} & z_{ac} & z_{an} \\ z_{ba} & z_{bb'} & z_{bc} & z_{bn} \\ z_{ca} & z_{cb} & z_{cc'} & z_{cn} \\ z_{na} & z_{nb} & z_{nc} & z_{nn'} \end{bmatrix} \qquad (5)$$

After the Z_{prim} matrix is reduced by Kron's equation assuming that the line has a multiple grounded neutral, the reduced form of the phase impedance matrix is represented (6).

$$[Z_{abc}] = \begin{bmatrix} Z_{aa'} & Z_{ab} & Z_{ac} \\ Z_{ba} & Z_{bb'} & Z_{bc} \\ Z_{ca} & Z_{cb} & Z_{cc'} \end{bmatrix} \qquad (6)$$

Most of the literature in the distribution system modeling in Europe is based on the sequence impedance of the line segments. The sequence impedance in a European LV feeder is represented by the zero (Z_0) and positive (Z_1) sequence impedances. The diagonal terms of the sequence impedance matrix are zero (Z_0), positive (Z_1) and negative (Z_2) sequence impedance. Z_1 and Z_2 are assumed to be equal for regular networks. Also, the following assumptions are made in order to model the system in the base of the sequence impedance:

- All self-impedances of the line should be equal, $Z_{aa'} = Z_{bb'} = Z_{cc'} = Z_s$
- All phase-to-phase mutual impedances should be equal, $Z_{ab} = Z_{ba} = Z_{ac} = Z_{ca} = Z_{bc} = Z_{cb} = Z_m$
- All phase-to-neutral mutual impedances should be equal, $Z_{an} = Z_{bn} = Z_{cn}$.

After the assumptions are adopted, the matrix Z_{abc} can be written as (7):

$$[Z_{abc}] = \begin{bmatrix} Z_s & Z_m & Z_m \\ Z_m & Z_s & Z_m \\ Z_m & Z_m & Z_s \end{bmatrix} \qquad (7)$$

The sequence impedance matrix can be created from equations (8) and (9):

$$[Z_{012}] = [A]^{-1} \cdot [Z_{abc}] \cdot [A] \qquad (8)$$

$$[A] = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix}, a = 1\angle120° \qquad (9)$$

$$[Z_{012}] = \begin{bmatrix} Z_s + 2 \cdot Z_m & 0 & 0 \\ 0 & Z_s - Z_m & 0 \\ 0 & 0 & Z_s - Z_m \end{bmatrix} \qquad (10)$$

Since diagonal elements of the sequence matrix (10) are Z_0, Z_1 and Z_2, they can be calculated from equations (11) and (12):

$$Z_0 = Z_s + 2 \cdot Z_m \qquad (11)$$

$$Z_1 = Z_2 = Z_s - Z_m \qquad (12)$$

As mentioned before, equations (5)-(12) describe the situation in distribution systems with the practice of earthing the neutral. Since not all distribution systems have the same practice, the effect of neutral cannot be neglected. Therefore, the authors in [30] proposed an impedance modeling that includes the impact of the neutral voltage. Equation (13) presents the proposed reduced matrix. Using the conversion formula (8) and assuming that all phase self-impedances are equal ($z_{aa'} = z_{bb'} = z_{cc'} = Z$) and $z_{nn'} = Z_n$, the new sequence impedance matrix (14) can be calculated.

$$[Z'_{abc}] = \begin{bmatrix} z_{aa'} + z_{nn'} & z_{nn'} & z_{nn'} \\ z_{nn'} & z_{bb'} + z_{nn'} & z_{nn'} \\ z_{nn'} & z_{nn'} & z_{cc'} + z_{nn'} \end{bmatrix} \qquad (13)$$

$$[Z'_{012}] = \begin{bmatrix} Z + 3 \cdot Z_n & 0 & 0 \\ 0 & Z & 0 \\ 0 & 0 & Z \end{bmatrix} \qquad (14)$$

E. End-user's Flexibility

As previously mentioned, end-users are becoming more important in energy transition because of the increase of LC technologies' share. DSOs must be able to adopt LC technologies on all voltage levels. Simultaneously they do not want to increase spending and invest in new overhead lines, cables, protective equipment, transformers, etc. Flexible end-users and end-users with shiftable loads can help the system operator avoid the investment into new equipment.

Authors in [33] propose a novel OPF method that solves the voltage issues with the help of battery storage and residential flexibility resources. [34] emphasizes the importance of the DER's aggregation in order to provide flexibility to power systems, while simultaneously flexibility providers can benefit from providing the service. A case study made in [35] shows that the investment in battery storage can become profitable by sharing and renting battery capacities with a DSO. A profit is achieved through incentives which are manifested through payments for providing ancillary services to the grid. In order to increase end-users' flexibility, [36] proposes dynamic prices for end-users, instead of the traditional pricing. The author in [37] considers electricity storage technologies and renewable generation curtailment as sources of flexibility in the power systems. Cost-effective renewable power curtailment takes place when, in correspondence with the excess generation, costs of shutting down and starting up conventional power plants are higher than the costs associated with renewable generation curtailment. Even though the marginal generation cost of RESs is zero, the curtailment of production power presents a financial loss for end-users if they are not encouraged through incentives. Research in [38] presents the benefits of providing flexibility inside an energy community. A coordinator agent provides community resources or power purchased from the grid if necessary. Providing flexibility in the energy community helps in minimizing the energy imported from the external grid and also enables profit in certain periods. Shifting the time of charge or bi-directional (V2G) charging of EVs can

provide balancing services. Authors in [39] show that savings are between 7% and 113% when EVs provide balancing services. The role of battery storage and demand response in providing flexibility is discussed in [40]. Authors showed that coordination of real storage of battery and virtual storage of building loads could produce substantial revenue and cost savings. A two-stage voltage regulation technique by utilizing the flexibility resources (FRs) is proposed in [41]. The first stage is the day-ahead scheduling, which optimally schedules the start time of FRs to minimize the electricity cost of customers and network voltage violation times. The second stage is the real-time operation, where the shifting method of FRs is proposed to ensure the voltage within the permissible range. The results show that the use of end-users' flexibility significantly reduces the use of OLTC transformers and that the voltage conditions are still ensured. Decentralized local energy trading in microgrids created in [42] shows that the proposed approach through the communication among the agents establishes the supply-demand balance in the microgrid and decides the energy trading prices, while simultaneously maintain all the node voltages within the safe operating limits.

Since the number of end-users providing flexibility is increasing, several local energy markets and trading mechanisms have been proposed and developed. Authors in [43] discussed the application of baselines and capacity limitations in the context of local flexibility markets in Europe. The research shows that baseline services do not meet the established requirements and that they are not compatible with the active participation of DERs in the power markets. The authors introduced capacity limitation services, which bypass many of the fundamental problems of baselines, in terms of service definition, verification, and the possibility of manipulation. The introduction The EcoGrid 2.0 project has designed and operated a fully functional local flexibility market, under real conditions [44]. The designing process includes the information and communications technology infrastructure, flexibility control strategies, aggregator prices models, and a verification and settlement methodology. The benefits of the previously mentioned baseline and capacity limitation services were assessed, to mitigate congestions in distribution networks. A case study made in the Norwegian network shows that the needed capacity problems caused by a rapid increase in the number of EVs could be solved with the local flexibility markets [45]. A framework for a decentralized local flexibility market at the distribution level, operating at the day-ahead (DA) and real-time (RT) was introduced in [46]. The contribution of the proposed framework lies in considering the uncertainty of demand in the DA period, which can affect the probability of congestion occurrence in RT operation. The authors proposed a probabilistic forecasting assessment process that is carried out by the DSO before calling for the flexibility market.

Besides developed flexibility markets, the number of peer-to-peer (P2P) trading mechanisms simultaneously develops. Authors in [47] compare community-based and decentralized P2P approaches of local energy markets in LV networks. The comparison presents different features and challenges for each approach. It is shown that both approaches can help with the integration of RESs in the LV network. The end-user benefits of electricity storage in the presence of P2P trade in local electricity markets with smart grid features are analyzed in [48]. The results of the two proposed market designs show that the different system configurations result in similar levels of savings for the electricity end-users.

F. Test Distribution Networks

In order to develop tools that will enable analyses and calculations test distribution networks should be created and developed. There is a number of synthetic and non-synthetic networks described in the literature which help in bringing conclusions regarding the occasions in the distribution networks.

Authors in [10] developed a model which creates both synthetic MV and LV distribution network. The modeled network is placed in Varaždin, Croatia. The network was created by comparing the results of the model with the indicators of the real distribution network in Varaždin, Croatia. A number of IEEE test feeders were developed in order to enable researches and different analyses [49], [50]. Authors in [30] used IEEE LV Test Feeder to draw conclusions from developing the impedance model which includes the impact of the neutral voltage. A set of 128 synthetic LV feeders based on real networks in the UK was developed by authors in [51]. Authors in [52], [53] present European reference network models in order to help regulators in the task of setting regulated revenues and performance incentives for distribution companies and to enable easier planning and analyses, e.g., PF calculations. An overview of the algorithms used to generate synthetic distribution systems using reference network models in the USA [54]. Heuristic methods are used to plan a large-scale distribution area, covering millions of consumers and hundreds of thousands of distribution transformers. At the same time, the systems are described in detail, all of the equipment is modeled for HV, MV, and LV levels. The system components that are included in the models are power lines, substations, distribution transformers, voltage regulators, capacitors, and switching devices.

Authors in [55] present a non-synthetic European low voltage test system. The paper presents all the required data for simulating a large European style LV with four-wire lines and a TT grounding system. The authors presented the raw data extracted from the areal GIS system of an electrical company and provide all the tools for analyzing the raw data and transforming them into a suitable OpenDSS model.

III. IMPACT OF LC TECHNOLOGIES ON THE LV NETWORK

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. Behind-the-meter LC technologies have impact on different PQ aspects that need to be analyzed and the violation of PQ parameters must be minimized.

A. Voltage Conditions

A high share of PVs in the MV or LV network can cause voltages with a magnitude that is higher than boundaries set by the grid code or the standards. [22] presents the optimal power flow (OPF)-based conservation voltage reduction (CVR)

operation in distribution networks with a high share of PVs. The proposed CVR scheme takes the advantage of 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 [56] propose different techniques for overvoltage prevention in LV networks: grid reinforcement, the application of active transformers, active power curtailment, reactive power management by PV inverters, demand response, and application of electrical energy storage systems (EESSs). The paper takes into consideration the impact of a PV battery storage system, which is one of the ways to mitigate the overvoltage. Results in [57] 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. Since the share of PV systems and EVs can cause voltage problems, it is important to find methods to avoid potential problems in the LV distribution network. Authors in [58] demonstrate that the overvoltages caused by PVs are slightly reduced by EVs and more importantly authors propose an 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. A novel method of battery energy storage system (BESS) power flow control to mitigate large voltage fluctuations resulting from the stochastic nature of PV power and improve PQ in regional distribution networks is presented in [59]. The authors also made analyses of the impact of other DGs, such as wind generators and the high penetration of EVs. They propose a fast real-time PF method that helps to analyze voltage conditions in networks with a high share of LC technologies. The study [60] investigates the smart PV inverter Volt/Var control in mitigating voltage violations due to high integration of PVs and increasing the PV hosting capacity of LV distribution networks. The results showed that typical PV inverters of the same size as the PV panels are unable to provide an adequate voltage regulation using Volt/Var control due to the priority given to real power generation and limited reactive power capability during peak irradiance. This problem was found to be alleviated using an oversized PV inverter as it effectively controls the voltage by enhancing its reactive power capability while delivering the peak power generation. In order to avoid voltage fluctuations in the LV distribution network caused by PVs, [61] proposes an advanced predictive voltage control for the tap operation of the voltage regulator. The proposed scheme is based on the estimation of short-time-ahead voltage values obtained with sensor measurement units. The scheme is an autonomous control scheme and does not require voltage values measured in RT, as in the centralized voltage control scheme. The proposed scheme can sufficiently prevent voltage violations without increasing the number of tap operations significantly to impact the operational lifetime of the voltage regulator.

B. Network Congestion

Another potential problem that can occur with a growing share of LC technologies in the distribution network is the overhead lines and cable congestion. The focus of [62] 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 the curtailment in a radial LV network. Studies in [63] investigated the EVs hosting capacity of different LV distribution networks in the UK. Analyses have shown that for some of the tested networks problems start at 40% penetration and it is mainly because of the transformer located at the substation, followed by thermal problems at the LV feeders. [64] presents a congestion forecast framework for visualization of the probability for the network congestion and the voltage deviation in a distribution network with a 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 the 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 HV networks [65]. The OTS control faces challenges during problematic days (high PV production, low demand when network problems cannot be mitigated. Authors in [66] 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 to OTS control. Results show that AD control overcomes the limitations of OTS control and allows mitigating all voltage and thermal issues. The work in [67] 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.

C. Voltage Unbalance

One of the biggest challenges in LV networks, related to PQ, is the voltage unbalance. Since most of the households have single-phase loads, even the existing situation, without installed PVs, battery storages, and EV chargers, results in voltage unbalance that exceeds the standard limitations [68]. A high number of single-phase LC technologies can increase the voltage unbalance in each node and the entire LV network. The stochastic approach, in which the PVs penetration level and output power are considered as random input variables shows that the 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 [69]. According to EN50160 [70] and IEC 61000-3-13 [71], 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 the three-phase connection of the PV system helps reducing voltage unbalance. Simulations in [72] 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 [73]. Both in [72], [73] authors observe the impact of only the PV system on the VUF, and the analyses are made for reference networks. However, the situation in the non-synthetic LV network could be different and there is a 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 a negative impact on equipment in the distribution network. Voltage unbalance can deteriorate the performance and reduce the 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 is 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 [74]. 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 the 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 [75]. A 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 [76]. When using the hybrid system of a PV and battery storage, it is possible to perform 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 compensates the deficiency [77]. Authors in [78] propose a voltage unbalance mitigation strategy to ensure the same stress among the resultant batteries' stress currents in all buses, along the whole feeder. Also, the authors design a central controller consisting of two PI-controllers for determining the required ratio of batteries' compensating currents in all nodes and with the control algorithm, the compensating currents among batteries in each phase on the same bus are redistributed in case of unavailable capacities/non-connected batteries on the same bus for ensuring the same stress. Authors emphasize the importance of

the investigation of the influence of redistributing the compensating batteries' stress currents of the whole feeder. 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 a potential loss of profit for the end-user. Authors in [79] 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. The phase load balancing (PLB) technique described in [80] presents the algorithm that consists of the identification of topology for the distribution network, uploading the input data, and the 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 [81] 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. Authors in [82] analyze the impact of different LC technologies' combination on the voltage unbalance. The voltage unbalance is analyzed according to General Summation Law described in IEC 61000-3-13 [71], meaning that it is observed in ten-minute intervals during the one week and in the whole LV network and not only in the end-users' node. The authors propose a unified balanced three-phase connection rule for the connection of behind-the-meter LC technologies to the LV network in order to reduce the impact of the voltage unbalance on the power system. Authors have defined the following scenarios of LC technologies connection:

- 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. The phase on which LC technologies are connected to each phase is randomly chosen for each node in Scenario 2. The three-phase connection of LC technologies is analyzed in Scenario 3. The referent scenario is named Initial, and in Initial scenario authors observe the voltage unbalance before the connection of LC technologies.

The authors defined four different cases, through which they observed the impact of the use of different LC technologies. Defined cases are:

- PVs-Case 1
- PVs and EVs-Case 2
- PVs, batteries (self-sufficiency), and EVs-Case 3
- PVs, batteries (cost minimization), and EVs-Case 4

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 LV network is analyzed over 128 weekly 10 minutes simulations. Fig. 2 and Fig. 3 show the interquartile range of the

value of the VUF in the case when end-users have installed PVs, EVs, and battery storages modeled as if end-users are active DA market participants for the share at 20% and 80%.

Results show that in all scenarios, when LC technologies are single-phase connected, the VUF values exceed the limitations set by standards [70], [71]. In the worst scenario of a single-phase connection, when all end-users are connected to the same phase at each node, the VUF goes as high as 70%. Besides the initial scenario, when there are no LC technologies in the observed network, Scenario 3, when LC technologies are three-phase connected is shown to be the preferable scenario from the DSO's perspective.

Fig. 4 and Fig. 5 show the frequency of the occurrence of the VUF that thresholds the 2% limitation in Case 4, for share at 20% and 80%. The results show that even at the share of

20%, the VUF violates the limitations more than it is allowed in all scenarios of single-phase connection of LC technologies. The results of Scenario 3 show that in the case of a three-phase connection of LC technologies, the limitations are not violated.

The conclusions of [82], but also some other papers [83]–[85] are that the three-phase connection should be used, whenever possible. Since the voltage unbalance is directly connected network losses (network losses increase by 4.1% for a 15% unbalance compared to a fully balanced system [81]) and higher network losses lead to financial losses, the DSOs should encourage the mitigation of the voltage unbalance since they would like to reduce, and not increase network and financial losses.
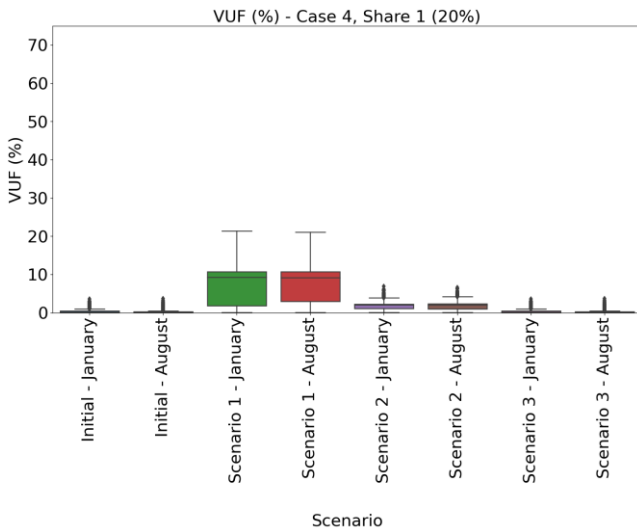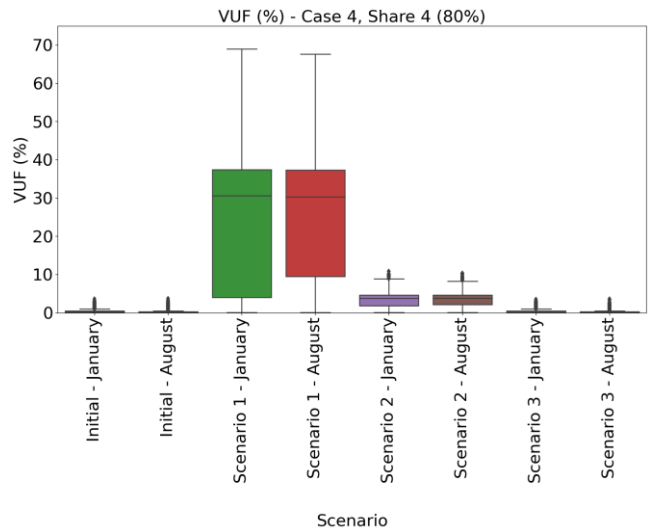

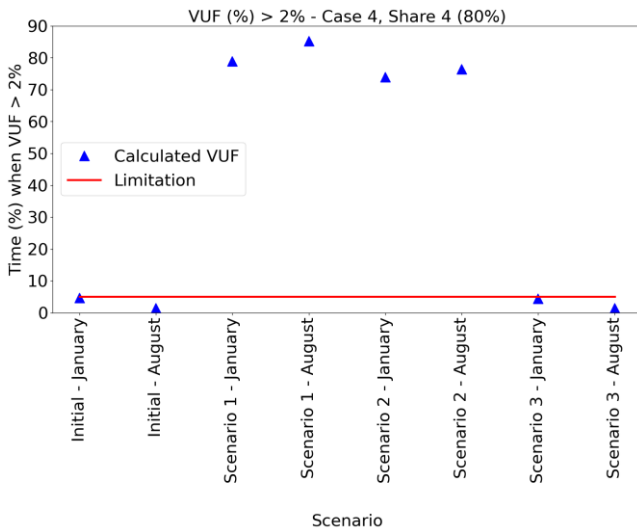Fig. 2 VUF (%)-Case 4; Share 1 (20%)

Fig. 3 VUF (%)-Case 4; Share 4 (80%)

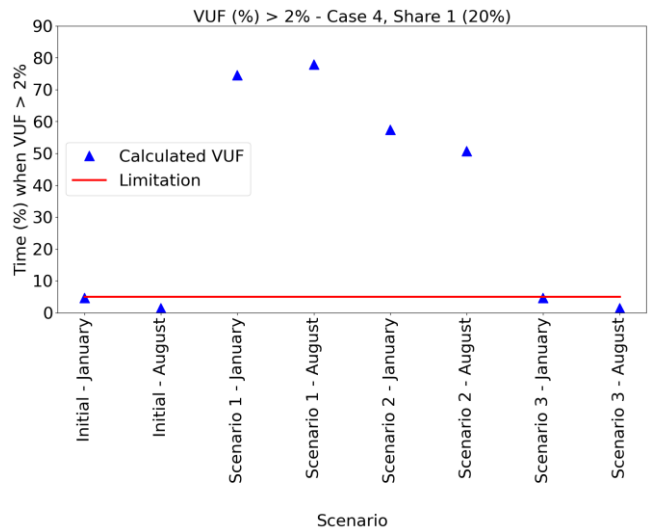
Fig. 4 VUF > 2%—Case 4; Share 1 (20%)

Fig. 5 VUF > 2%—Case 4; Share 4 (80%)

D. Other Voltage, Current and PQ Issues

With the continuous growth of the share of LC technologies in the distribution network, satisfying PQ is becoming a more challenging task. Each of the PQ parameters has boundaries that must not be violated. Analyses in [86] quantify variations of voltage, frequency, and power factor monthly in a year 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 profiles were examined to find the 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 [22], [56]–[58]. Authors in [87] 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 in 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 [88], all of the measured PV systems had significantly different harmonic patterns, which makes it difficult to propose simplified values for modeling without measuring and analyzing a greater number of devices. It is important to emphasize the difference between site measurements and laboratory tests with controlled harmonic voltage conditions [89]. 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 a power system with a high share of renewable energy sources, 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 the energy storage system (ESS) could help to avoid the PQ problems, such as overvolt-age, network congestion, harmonic distortion, voltage unbalance, etc., caused by penetration of RESs [90]. 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 [91]. 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 smart charging can help to mitigate PQ problems. In the case study shown in [92], 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 reschedules charging loads of EVs using the deterministic programming algorithm based on historical data to maintain network constraints within their boundaries [93]. 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 the 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 2030, voltage fluctuations will no longer be major problems, and by 2050, EVs will be able to limit fluctuations in residual loads to low values [94].

IV. CONCLUSIONS AND THE FUTURE WORK

This paper provides a brief review of the impact of end-users with the high share of LC technologies on the distribution system, especially the LV network. Since the planning and operation became more demanding because of the intermittent and unpredictable LC technologies, the development of new tools, that will help the DSOs, has become more important. A significant role in the energy transition has been given to GIS tools, which besides traditional analyses, enable a geospatial analysis of the power system. GIS tools are used for planning the system, creating a reference network, a visualization of PF calculations, etc. New planning approaches take into consideration the configuration of LV networks and the proposed methods that have a goal of increasing RESs' hosting capacities, newly developed stochastic and approximation methods, etc.

Besides the unpredictable and intermittent behavior of LC technologies, the other significant reason for the increased need for the development of tools is the configuration and the structure of distribution networks. The additional problem present LV networks, since they are four-wired and three-phased. Because of that, the traditional PF methods were not appropriate since they did not guarantee the convergence and the solution in each tested case. Therefore, a significant number of new methods have been developed, and already developed, traditional methods have been improved. The same practice has been adopted for OPF calculations that are becoming more challenging in LV networks, because of the end-users' flexibility, characteristics of LC technologies, a higher number of balancing groups, etc. In order to verify different methods, tools, and to make different analyses, a large number of reference and synthetic networks has been developed. Reference and synthetic present networks with the parameters that adequately describe the real-world network.

The other important aspect of the power system's analyses is analyses of PQ in distribution networks. A significant number of PVs cause overvoltages in periods when the production is high, and end-users cannot consume the energy in the same period. High penetration of EVs can cause the occurrence of undervoltages when more EV chargers are installed in the

same circuit and end-users simultaneously charge their EVs. Even though end-users are three-phase connected to the network, especially in urban networks, their devices are single-phase, i.e., even without the integration of LC technologies, a voltage unbalance occurs at the end-users' nodes. When the end-users decide to invest in single-phase LC technologies, a voltage unbalance increases and causes additional network losses. Several research studies showed that the three-phase connection of LC technologies should be adopted whenever possible since it mitigates the voltage unbalance problems. Other problems caused by LC technologies in distribution systems are related to network congestion, harmonic distortion, flickers, etc.

In future work, new tools for the PQ parameters assessment will be developed. The emphasis will be on integrating the assessment of multiple PQ parameters, such as the VUF, voltage unbalance, harmonic distortion, flickers, etc. in one tool. Since the further integration of LC technologies is inevitable and it is already shown in the current studies that a high number of LC technologies can lead to problems related to the equipment's performance, network and financial losses, etc., new methods for the minimization of harmful effects of LC technologies will be developed. Finally, a financial aspect of providing the satisfactory PQ will be investigated and methods that will encourage end-users to help the power system in terms of PQ will be developed.

V. ACKNOWLEDGMENT

VI. REFERENCES

[1] "2030 Climate Target Plan." [Online]. Available: https://ec.europa.eu/clima/policies/eu-climate-action/2030_ctp_en. [Accessed: 13-Jan-2021].

[2] "2030 Climate & Energy Framework." [Online]. Available: https://ec.europa.eu/clima/policies/strategies/2030_en. [Accessed: 09-Jan-2020].

[3] "2050 Long-Term Strategy." [Online]. Available: https://ec.europa.eu/clima/policies/strategies/2050_en. [Accessed: 09-Jan-2020].

[4] A. Jäger-Waldau, "PV Status Report 2019," 2019.

[5] International Renewable Energy Agency, *Electricity Storage and Renewables: Costs and Markets to 2030 Electricity Storage and Renewables: Costs and Markets to 2030*. Abu Dhabi, UAE, 2017.

[6] A. T. Procopiou *et al.*, "On the role of integrated MV-LV network modelling in DER studies," 2020, no. September, pp. 1–5.

[7] J. Quirós-Tortós, G. Valverde, A. Argüello, and L. N. Ochoa, "Geo-Information Is Power: Using Geographical Information Systems to Assess Rooftop Photovoltaics in Costa Rica," *IEEE Power Energy Mag.*, vol. 15, no. 2, pp. 48–56, 2017.

[8] G. Custodio, F. C. L. Trindade, K. Petrou, and L. F. Ochoa, "An Advanced GIS-based Tool for the Analysis of Future Distribution Networks," *2019 IEEE PES Conf. Innov. Smart Grid Technol. ISGT Lat. Am. 2019*, no. September, 2019.

[9] T. Antic, T. Capuder, M. Zidar, J. Graso, and A. Marusic, "Integrated Distribution Network Planning Tool Supported by Geographical Information System," *iSPEC 2019 - 2019 IEEE Sustain. Power Energy Conf. Grid Mod. Energy Revolution, Proc.*, pp. 2270–2275, 2019.

[10] M. Grzanic, M. G. Flammini, and G. Prettico, "Distribution network model platform: A first case study," *Energies*, vol. 12, no. 21, 2019.

[11] M. Gržanić, T. Antić, M. G. Flammini, H. Wilkening, and G. Prettico, "Renewable energies integration in a DiNeMo model based on a German urban grid," in *CIRED 2020 Berlin Workshop*, 2020.

[12] K. Kaippilly Radhakrishnan, J. Moirangthem, S. K. Panda, and G. Amaratunga, "GIS Integrated Automation of a Near Real-Time Power-Flow Service for Electrical Grids," *IEEE Trans. Ind. Appl.*, vol. 54, no. 6, pp. 5661–5670, 2018.

[13] J. Quirós-Tortós and L. F. Ochoa, "Multi-year planning of LV networks with EVs accounting for customers, emissions and techno-economics aspects: A practical and scalable approach," *IET Gener. Transm. Distrib.*, no. November, 2020.

[14] W. Niederhuemer and R. Schwalbe, "Increasing PV hosting capacity in LV grids with a probabilistic planning approach," *Proc. - 2015 Int. Symp. Smart Electr. Distrib. Syst. Technol. EDST 2015*, pp. 537–540, 2015.

[15] G. Ye *et al.*, "Planning of PV-ESS System for Distribution Network Considering PV Penetration," *2020 IEEE 3rd Int. Conf. Electron. Technol. ICET 2020*, pp. 339–343, 2020.

[16] L. Hou, Y. Chen, K. Su, Y. Wang, and Z. Zhang, "Research on Bi-level Planning Method of Active Distribution Network Considering Flexible Interconnection of Source Network Load and Storage," *iSPEC 2019 - 2019 IEEE Sustain. Power Energy Conf. Grid Mod. Energy Revolution, Proc.*, pp. 45–49, 2019.

[17] B. Sereeter, K. Vuik, and C. Witteveen, "Newton power flow methods for unbalanced three-phase distribution networks," *Energies*, vol. 10, no. 10, 2017.

[18] T. Alinjak, I. Pavic, and K. Trupinic, "Improved three-phase power flow method for calculation of power losses in unbalanced radial distribution network," *CIRED - Open Access Proc. J.*, vol. 2017, no. 1, pp. 2361–2365, 2017.

[19] A. Kotsonias, L. Hadjidemetriou, and E. Kyriakides, "Power Flow for a Four-Wire Radial Low Voltage Distribution Grid with a Single Point Grounded Neutral," *Proc. 2019 IEEE PES Innov. Smart Grid Technol. Eur. ISGT-Europe 2019*, 2019.

[20] Z. Xiaoyan *et al.*, "Three-phase Power Flow Model of

Low-voltage Distribution Network Considering Phase Asymmetry and Photovoltaic Access," *iSPEC 2019 - 2019 IEEE Sustain. Power Energy Conf. Grid Mod. Energy Revolution, Proc.*, pp. 1438–1443, 2019.

[21] U. H. Ramadhani, M. Shepero, J. Munkhammar, J. Widén, and N. Etherden, "Review of probabilistic load flow approaches for power distribution systems with photovoltaic generation and electric vehicle charging," *Int. J. Electr. Power Energy Syst.*, vol. 120, no. February, p. 106003, 2020.

[22] L. Gutierrez-Lagos and L. F. Ochoa, "OPF-Based CVR Operation in PV-Rich MV-LV Distribution Networks," *IEEE Trans. Power Syst.*, vol. 34, no. 4, pp. 2778–2789, 2019.

[23] I. I. Avramidis, F. Capitanescu, and G. Deconinck, "Practical approximations and heuristic approaches for managing shiftable loads in the multi-period optimal power flow framework," *Electr. Power Syst. Res.*, vol. 190, no. July 2020, p. 106864, 2021.

[24] I. I. Avramidis, F. Capitanescu, and G. Deconinck, "A Comprehensive Multi-Period Optimal Power Flow Framework for Smart LV Networks," *IEEE Trans. Power Syst.*, no. November, 2020.

[25] I. I. Avramidis, F. Capitanescu, and G. Deconinck, "A generic multi-period optimal power flow framework for combating operational constraints via residential flexibility resources," *IET Gener. Transm. Distrib.*, no. December, 2020.

[26] G. X. Luo and A. Semlyen, "Efficient load flow for large weakly meshed networks," *IEEE Trans. Power Syst.*, vol. 5, no. 4, pp. 1309–1316, 1990.

[27] C. S. Cheng and D. Shirmohammadi, "A three-phase power flow method for real-time distribution system analysis," *IEEE Trans. Power Syst.*, vol. 10, no. 2, pp. 671–679, 1995.

[28] T. Chen, M. Chen, P. Kotas, and E. A. Chebli, "Distribution System Power Flow Analysis - A Rigid Approach," *IEEE Trans. Power Deliv.*, vol. 6, no. 3, pp. 1146–1152, 1991.

[29] M. F. AlHajri and M. E. El-Hawary, "Exploiting the radial distribution structure in developing a fast and flexible radial power flow for unbalanced three-phase networks," *IEEE Trans. Power Deliv.*, vol. 25, no. 1, pp. 378–389, 2010.

[30] A. Koirala, R. D'Hulst, and D. Van Hertem, "Impedance modelling for European style Distribution Feeder," *SEST 2019 - 2nd Int. Conf. Smart Energy Syst. Technol.*, 2019.

[31] W. H. Kersting and W. H. Phillips, "Distribution Feeder Line Models," *IEEE Trans. Ind. Appl.*, vol. 31, no. 4, pp. 715–720, 1995.

[32] W. H. Kersting, *Distribution System Modelling and Analysis*. CRC Press LLC, 2002.

[33] I. I. Avramidis, F. Capitanescu, and G. Deconinck, "On the contributions of operational flexibility offered by smart sustainable residential buildings," *IEEE PES Innov. Smart Grid Technol. Conf. Eur.*, vol. 2020-Octob, no. October, pp. 834–838, 2020.

[34] I. Pavić, M. Beus, and I. Androček, "Impact of an Aggregator of Distributed Energy Resources on Traditional Power System Participants," in *CIRED 2018 Ljubljana Workshop*, 2018.

[35] M. Grzanic, T. Capuder, and S. Krajcar, "DSO and Aggregator Sharing Concept for Distributed Battery Storage System," *Proc. - 2018 IEEE Int. Conf. Environ. Electr. Eng. 2018 IEEE Ind. Commer. Power Syst. Eur. EEEIC/I CPS Eur. 2018*, 2018.

[36] M. Grzanic and T. Capuder, "The Value of Prosumers' Flexibility under Different Electricity Market Conditions: Case Studies of Denmark and Croatia," *2019 IEEE PES GTD Gd. Int. Conf. Expo. Asia, GTD Asia 2019*, pp. 616–621, 2019.

[37] A. Spisto, "Impact of flexible technologies on end-users' price under different levels of renewable generation," *Int. Conf. Eur. Energy Mark. EEM*, vol. 2016-July, pp. 1–5, 2016.

[38] I. F. G. Reis, I. Goncalves, M. A. R. Lopes, and C. H. Antunes, "Residential demand-side flexibility in energy communities: A combination of optimization and agent modeling approaches," in *SEST 2019 - 2nd International Conference on Smart Energy Systems and Technologies*, 2019.

[39] S. Canevese, D. Cirio, M. Gallanti, and A. Gatti, "EV Flexibility Supply via Participation in Balancing Services: Possible Profitability for Italian End Users," *2019 AEIT Int. Annu. Conf. AEIT 2019*, 2019.

[40] H. Hao, D. Wu, J. Lian, and T. Yang, "Optimal Coordination of Building Loads and Energy Storage for Power Grid and End User Services," *IEEE Trans. Smart Grid*, vol. 9, no. 5, pp. 4335–4345, 2018.

[41] Q. Xie *et al.*, "Use of demand response for voltage regulation in power distribution systems with flexible resources," *IET Gener. Transm. Distrib.*, vol. 14, no. 5, pp. 883–892, 2020.

[42] A. Paudel, M. Khorasany, and H. B. Gooi, "Decentralized Local Energy Trading in Microgrids with Voltage Management," *IEEE Trans. Ind. Informatics*, vol. 17, no. 2, pp. 1111–1121, 2021.

[43] C. Ziras, C. Heinrich, and H. W. Bindner, "Why baselines are not suited for local flexibility markets," *Renew. Sustain. Energy Rev.*, vol. 135, no. December 2019, p. 110357, 2021.

[44] C. Heinrich, C. Ziras, A. L. A. Syrri, and H. W. Bindner, "EcoGrid 2.0: A large-scale field trial of a local flexibility market," *Appl. Energy*, vol. 261, no. March, 2020.

[45] I. Ilieva and B. Bremdal, "Implementing local flexibility markets and the uptake of electric vehicles - The case for Norway," *6th IEEE Int. Energy Conf. ENERGYCon 2020*, pp. 1047–1052, 2020.

[46] A. Esmat, J. Usaola, and M. Á. Moreno, "A decentralized local flexibility market considering the uncertainty of demand," *Energies*, vol. 11, no. 8, 2018.

[47] J. Guerrero, A. C. Chapman, and G. Verbič, "Local energy markets in LV networks: Community based and decentralized P2P approaches," *2019 IEEE Milan*

PowerTech, PowerTech 2019, 2019.

[48] A. Lüth, J. M. Zepter, P. Crespo del Granado, and R. Egging, "Local electricity market designs for peer-to-peer trading: The role of battery flexibility," *Appl. Energy*, vol. 229, no. August, pp. 1233–1243, 2018.

[49] K. P. Schneider *et al.*, "Analytic Considerations and Design Basis for the IEEE Distribution Test Feeders," *IEEE Trans. Power Syst.*, vol. 33, no. 3, pp. 3181–3188, 2018.

[50] "IEEE PES distribution system analysis subcommittee's distribution test feeder working group." [Online]. Available: https://site.ieee.org/pes-testfeeders/resources/. [Accessed: 08-Jan-2021].

[51] V. Rigoni, L. F. Ochoa, G. Chicco, A. Navarro-Espinosa, and T. Gozel, "Representative residential LV feeders: A case study for the North West of England," *IEEE Trans. Power Syst.*, vol. 31, no. 1, pp. 348–360, 2016.

[52] T. Gómez, C. Mateo, Á. Sánchez, P. Frías, and R. Cossent, "Reference Network Models: A Computational Tool for Planning and Designing Large-Scale Smart Electricity Distribution Grids," in *High Performance Computing in Power and Energy Systems*, vol. 76, S. K. Khaitan and A. Gupta, Eds. Berlin: Springer Berlin Heidelberg, 2013, pp. 247–279.

[53] C. Mateo Domingo, T. Gómez San Román, Á. Sánchez-Miralles, J. P. Peco González, and A. Candela Martínez, "A reference network model for large-scale distribution planning with automatic street map generation," *IEEE Trans. Power Syst.*, vol. 26, no. 1, pp. 190–197, 2011.

[54] C. Mateo *et al.*, "Building Large-Scale U.S. Synthetic Electric Distribution System Models," *IEEE Trans. Smart Grid*, vol. 11, no. 6, pp. 5301–5313, 2020.

[55] A. Koirala, L. Suárez-Ramón, B. Mohamed, and P. Arboleya, "Non-synthetic European low voltage test system," *Int. J. Electr. Power Energy Syst.*, vol. 118, no. September 2019, p. 105712, 2020.

[56] S. Hashemi and J. Østergaard, "Methods and strategies for overvoltage prevention in low voltage distribution systems with PV," *IET Renew. Power Gener.*, vol. 11, no. 2, pp. 205–214, 2017.

[57] J. D. Watson, N. R. Watson, D. Santos-Martin, A. R. Wood, S. Lemon, and A. J. V. Miller, "Impact of solar photovoltaics on the low-voltage distribution network in New Zealand," *IET Gener. Transm. Distrib.*, vol. 10, no. 1, pp. 1–9, 2016.

[58] J. F. Franco, A. T. Procopiou, J. Quirós-Tortós, and L. F. Ochoa, "Advanced control of OLTC-enabled LV networks with PV systems and EVs," *IET Gener. Transm. Distrib.*, vol. 13, no. 14, pp. 2967–2975, 2019.

[59] M. M. Biswas, S. R. Akhter, and K. C. Paul, "Power Quality Analysis for Distributed Generation and Electric Vehicle Integrated Distribution System," *UPEC 2020 - 2020 55th Int. Univ. Power Eng. Conf. Proc.*, no. October, pp. 4–10, 2020.

[60] D. Almeida, J. Pasupuleti, J. Ekanayake, and E. Karunarathne, "Mitigation of overvoltage due to high penetration of solar photovoltaics using smart inverters volt/var control," *Indones. J. Electr. Eng. Comput. Sci.*, vol. 19, no. 3, pp. 1259–1266, 2020.

[61] S. Yoshizawa and Y. Hayashi, "Advanced voltage control based on short-time ahead voltage fluctuation estimation in distribution system," *Electr. Power Syst. Res.*, vol. 188, no. July, p. 106559, 2020.

[62] A. N. M. M. Haque, M. T. Rahman, P. H. Nguyen, and F. W. Bliek, "Smart curtailment for congestion management in LV distribution network," *IEEE Power Energy Soc. Gen. Meet.*, vol. 2016-Novem, 2016.

[63] J. Quirós-Tortós, L. Ochoa, and T. Butler, "How electric vehicles and the grid work together: Lessons learned from one of the largest electric vehicle trials in the world," *IEEE Power Energy Mag.*, vol. 16, no. 6, pp. 64–76, 2018.

[64] A. Srivastava, D. Steen, L. A. Tuan, and O. Carlson, "A congestion forecast framework for distribution systems with high penetration of PVs and PEVs," *2019 IEEE Milan PowerTech, PowerTech 2019*, no. 773717, pp. 1–6, 2019.

[65] K. Petrou *et al.*, "Limitations of Residential Storage in PV-Rich Distribution Networks: An Australian Case Study," *IEEE Power Energy Soc. Gen. Meet.*, vol. 2018-Augus, no. August, 2018.

[66] A. T. Procopiou, K. Petrou, L. F. Ochoa, T. Langstaff, and J. Theunissen, "Adaptive decentralized control of residential storage in pv-rich mv-lv networks," *IEEE Trans. Power Syst.*, vol. 34, no. 3, pp. 2378–2389, 2019.

[67] A. T. Procopiou and L. F. Ochoa, "Adaptive asset congestion management in PV-rich LV networks," *2019 IEEE Milan PowerTech, PowerTech 2019*, no. June, 2019.

[68] D. Rusinaru, L. G. Manescu, M. Ciontu, and M. Alba, "Three-phase load flow analysis of the unbalanced distribution networks," *2016 Int. Conf. Appl. Theor. Electr. ICATE 2016 - Proc.*, pp. 1–5, 2016.

[69] A. Kharrazi, V. Sreeram, and Y. Mishra, "Assessment of voltage unbalance due to single phase rooftop photovoltaic panels in residential low voltage distribution network: A study on a real LV network in Western Australia," *2017 Australas. Univ. Power Eng. Conf. AUPEC 2017*, vol. 2017-Novem, no. October, pp. 1–6, 2018.

[70] H. Markiewicz and A. Klajn, "Voltage Disturbances - Standard EN 50160," p. 17, 2006.

[71] "IEC 61000-3-13 Electromagnetic compatibility (EMC) – Part 3-13: Limits – Assessment of emission limits for the connection of unbalanced installations to MV, HV and EHV power systems." 2015.

[72] F. Rezvani, B. Mozafari, and F. Faghihi, "Power quality analysis for Photovoltaic system considering unbalanced voltage," *Indian J. Sci. Technol.*, vol. 8, no. 14, 2015.

[73] A. Lucas, "Single-phase PV power injection limit due

to voltage unbalances applied to an urban reference network using real-time simulation," *Appl. Sci.*, vol. 8, no. 8, 2018.

[74] I. Plummer, "Asymmetry in Distribution Systems: Causes, Harmful Effects and Remedies," Lousiana State University, Baton Rouge, LA, USA, 2011.

[75] K. H. Chua, Y. S. Lim, J. Wong, P. Taylor, E. Morris, and S. Morris, "Voltage Unbalance Mitigation in Low Voltage Distribution Networks with Photovoltaic Systems," *J. Electron. Sci. Technol.*, vol. 10, no. 1, pp. 1–6, 2012.

[76] M. G. Lopes, F. C. L. Trindade, and L. F. Ochoa, "Phase-to-Phase Connection of PV Systems in Brazilian LV Networks: Modelling and Impacts," *2019 IEEE PES Conf. Innov. Smart Grid Technol. ISGT Lat. Am. 2019*, pp. 1–6, 2019.

[77] A. M. M. Nour, A. Y. Hatata, A. A. Helal, and M. M. El-Saadawi, "Rooftop PV systems with distributed batteries for voltage unbalance mitigation in low voltage radial feeders," *J. Renew. Sustain. Energy*, vol. 10, no. 5, 2018.

[78] A. M. M. Nour, A. A. Helal, M. M. El-Saadawi, and A. Y. Hatata, "A control scheme for voltage unbalance mitigation in distribution network with rooftop PV systems based on distributed batteries," *Int. J. Electr. Power Energy Syst.*, vol. 124, no. April 2020, p. 106375, 2021.

[79] N. Safitri, F. Shahnia, and M. A. S. Masoum, "Coordination of single-phase rooftop pvs in unbalanced three-phase residential feeders for voltage profiles improvement," *Aust. J. Electr. Electron. Eng.*, vol. 13, no. 2, pp. 77–90, 2016.

[80] G. Grigoraş, B. C. Neagu, M. Gavrilaş, I. Trişţiu, and C. Bulac, "Optimal phase load balancing in low voltage distribution networks using a smart meter data-based algorithm," *Mathematics*, vol. 8, no. 4, 2020.

[81] L. F. Ochoa, R. M. Ciric, A. Padilha-Feltrin, and G. P. Harrison, "Evaluation of distribution system losses due to load unbalance," *15th Power Syst. Comput. Conf. PSCC 2005*, no. August, 2005.

[82] 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. 30, 2021.

[83] C. G. Bajo, S. Hashemi, S. B. Kjsar, G. Yang, and J. Ostergaard, "Voltage unbalance mitigation in LV networks using three-phase PV systems," *Proc. IEEE Int. Conf. Ind. Technol.*, vol. 2015-June, no. June, pp. 2875–2879, 2015.

[84] D. V. Bozalakov, J. Laveyne, J. Desmet, and L. Vandevelde, "Overvoltage and voltage unbalance mitigation in areas with high penetration of renewable energy resources by using the modified three-phase damping control strategy," *Electr. Power Syst. Res.*, vol. 168, pp. 283–294, Mar. 2019.

[85] J. Nájera, H. Mendonça, R. M. De Castro, and J. R. Arribas, "Strategies comparison for voltage unbalance

mitigation in LV distribution networks using EV chargers," *Electronics*, vol. 8, no. 3, 2019.

[86] W. Miller, A. Liu, Z. Amin, and A. Wagner, "Power quality and rooftop-photovoltaic households: An examination of measured data at point of customer connection," *Sustain.*, vol. 10, no. 4, pp. 1–27, 2018.

[87] H. H. H. De Silva, D. K. J. S. Jayamaha, and N. W. A. Lidula, "Power Quality Issues Due to High Penetration of Rooftop Solar PV in Low Voltage Distribution Networks: A Case Study," *2019 IEEE 14th Int. Conf. Ind. Inf. Syst. Eng. Innov. Ind. 4.0, ICIIS 2019 - Proc.*, no. January 2020, pp. 395–400, 2019.

[88] J. Niitsoo, M. Jarkovoi, P. Taklaja, J. Klüss, and I. Palu, "Power Quality Issues Concerning Photovoltaic Generation in Distribution Grids," *Smart Grid Renew. Energy*, vol. 06, no. 06, pp. 148–163, 2015.

[89] J. Schlabbach and A. Gross, "Harmonic current emission of photovoltaic inverters," no. April 2007, 2016.

[90] C. K. Das, O. Bass, G. Kothapalli, T. S. Mahmoud, and D. Habibi, "Overview of energy storage systems in distribution networks: Placement, sizing, operation, and power quality," *Renew. Sustain. Energy Rev.*, vol. 91, no. November 2016, pp. 1205–1230, 2018.

[91] M. Tadjine, T. Allaoui, B. Belabbas, and M. Denai, "Power quality enhancement in hybrid photovoltaic-battery system based on three-level inverter associated with DC bus voltage control," *J. Power Technol.*, vol. 97, no. 4, pp. 272–282, 2017.

[92] V. Monteiro, H. Gonçalves, and J. L. Afonso, "Impact of electric vehicles on power quality in a Smart Grid context," *Proceeding Int. Conf. Electr. Power Qual. Util. EPQU*, no. October 2014, pp. 660–665, 2011.

[93] M. J. M. Al Essa, "Power Quality of Electrical Distribution Systems Considering PVs, EVs and DSM," *J. Control. Autom. Electr. Syst.*, no. 2016, 2020.

[94] N. B. G. (Nico. Brinkel *et al.*, "Impact of rapid PV fluctuations on power quality in the low-voltage grid and mitigation strategies using electric vehicles," *Int. J. Electr. Power Energy Syst.*, vol. 118, no. November 2019, p. 105741, 2020.