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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 Section 2. A definition of each case study and the differences between them are presented in Section 3. The results of analyses are shown and discussed in Section 4. In Section 5, 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, Section 6 gives the conclusions and directions for future work.

2. Power quality — definitions and mathematical model

As mentioned in Section 1, 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).

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

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

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 in Table 1.

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 Section 1, 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 in Fig. 1 contains 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

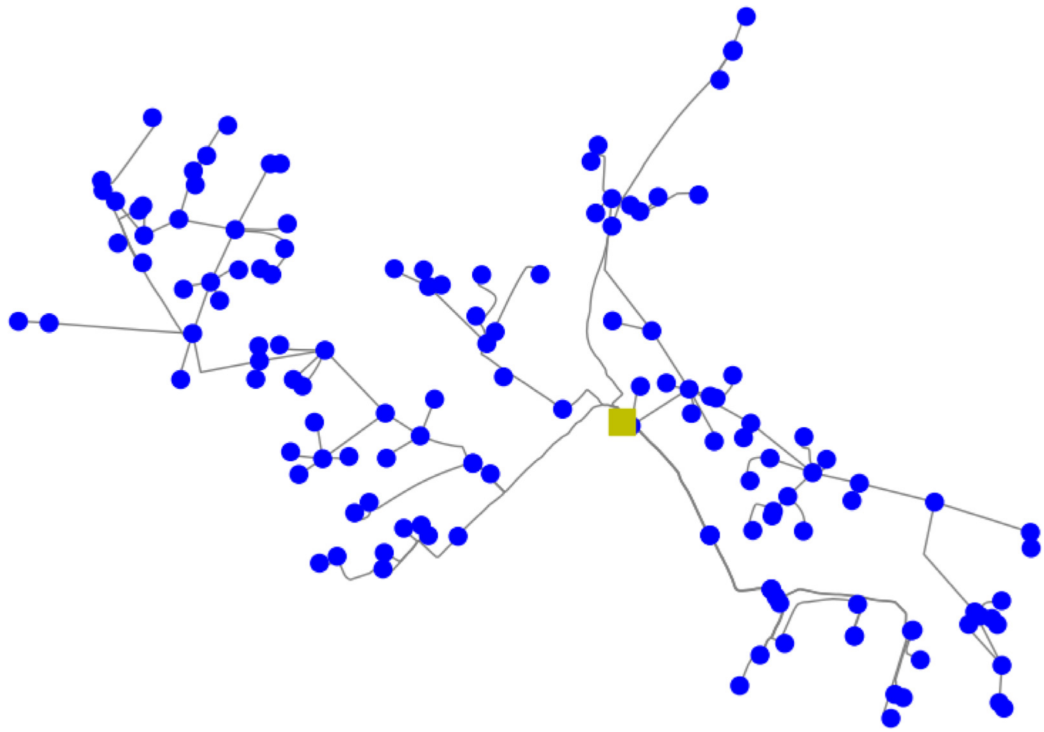

Fig. 1. A residential LV network.

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 Section 4, 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. 2 shows 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 from Fig. 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 in Fig. 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 inf Fig. 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 in Fig. 4 show 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

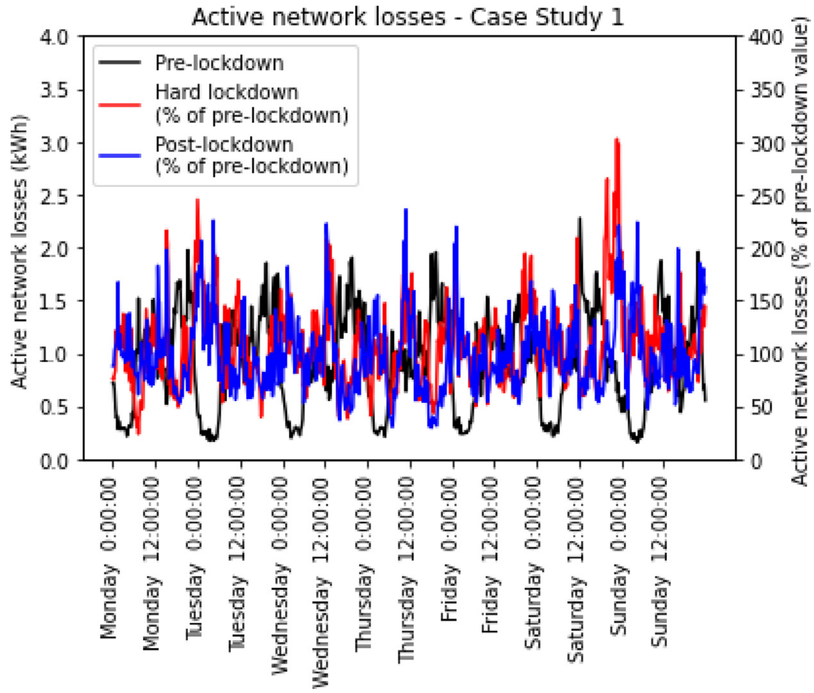

Fig. 2. Active network losses (kWh) - CS1.

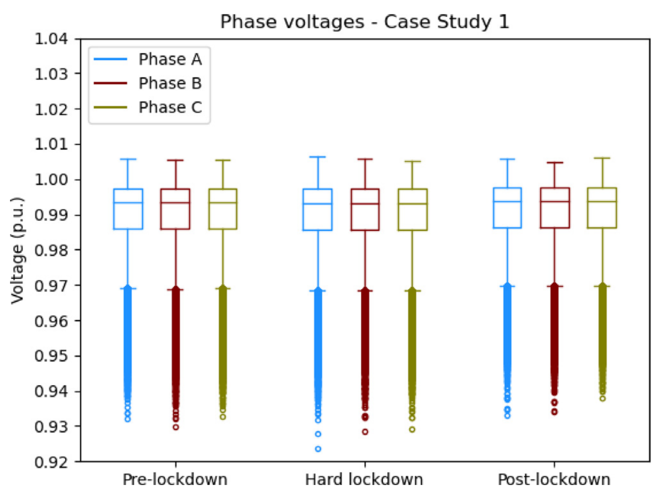

Fig. 3. Phase voltages ($p.u.$) - CS1.

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 in Fig. 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 in Fig. 5.

As it can be seen in Fig. 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 Section 2 shows 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 in Fig. 6.

As it can be seen in Fig. 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

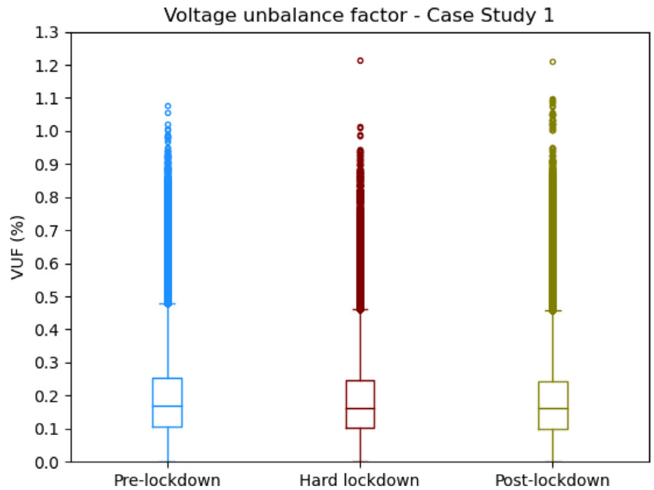

Fig. 4. Voltage unbalance facotr (%) - CS1.

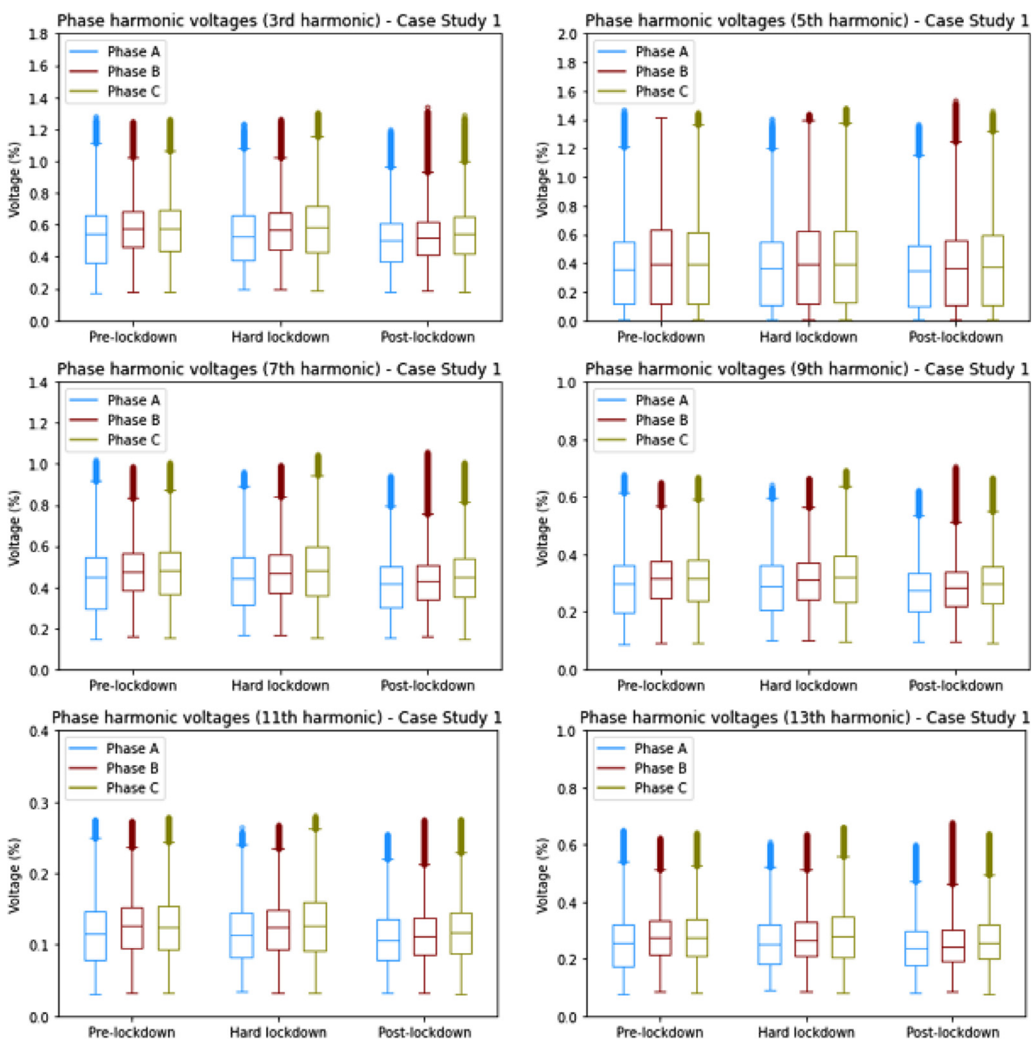

Fig. 5. Phase harmonic voltages (%) - CS1.

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

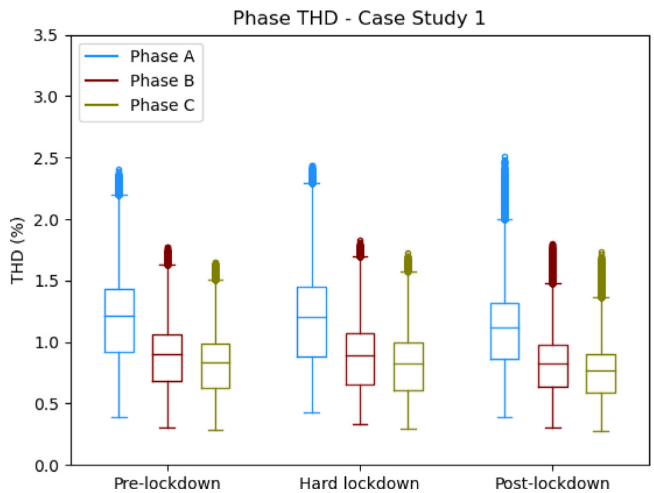

Fig. 6. THD (%) - CS1.

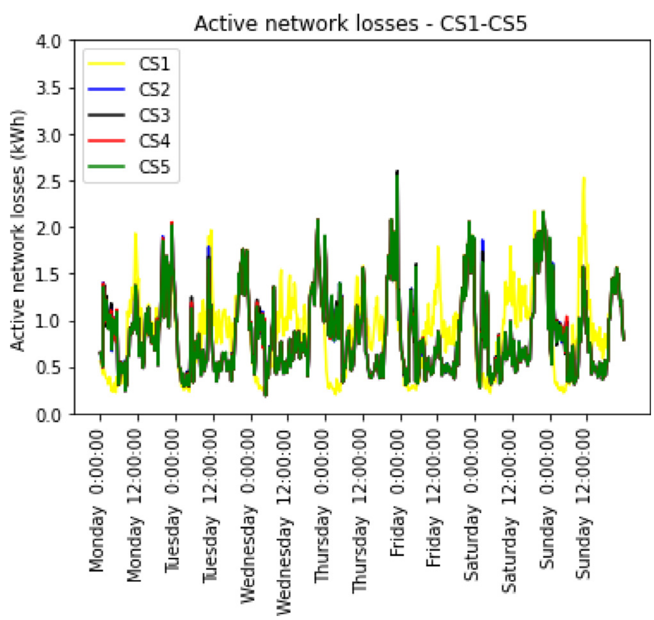

Fig. 7. Active network losses — CS1–CS5.

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 Section 3. 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 in Fig. 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 in Fig. 7 are 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

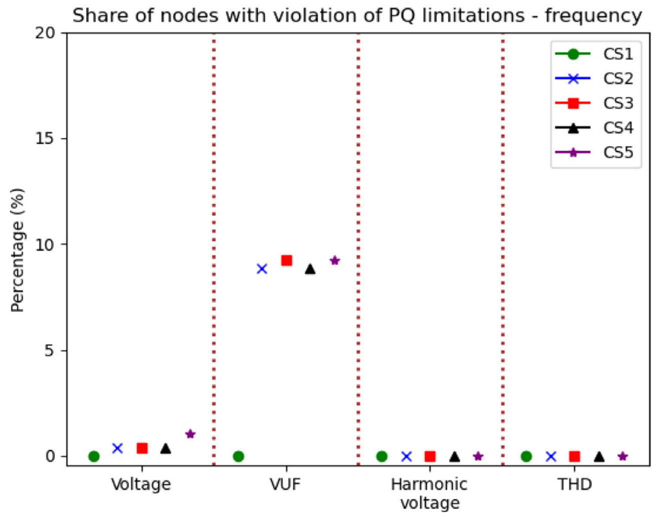

Fig. 8. Share of nodes with violation of PQ limitations — frequency.

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.

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

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

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

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

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

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

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

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 infrastructure
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 in Fig. 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 Section 4. 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 in Fig. 9.

Table 3 shows 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.

Table 3 shows the results of the PQ improvement in terms of the frequency of violating technical constraints. As it can be seen from the results in Table 3, 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

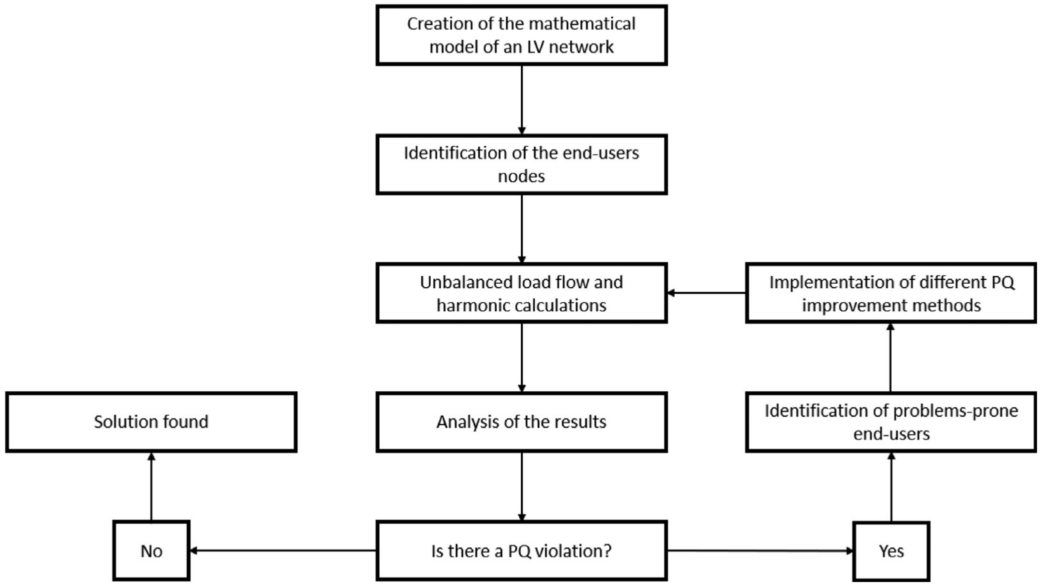

Fig. 9. Improvement of PQ — methodology.

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 in Table 4.

The conclusions that can be drawn from the results presented in Table 4 are 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, Tables 5 and 6 show 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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