ISSN 2004-2965 Energy Proceedings, Vol. 24, 2021

International Conference on Applied Energy 2021
Nov. 29 - Dec. 2, 2021, in Bangkok, Thailand
Paper ID: 0268

GIS visualization of COVID-19 impact on PQ indicators in distribution networks: A case study of Croatia

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ABSTRACT

A large part of 2020 and 2021 was marked by the COVID-19 pandemic. A global pandemic has caused changes in people's behavior and has created challenges for multiple industries and numerous sectors. One of the most affected sectors is the electricity sector, which already deals with challenges caused by decarbonization and the integration of low-carbon technologies. Newly caused challenges are especially important for Distribution System Operators (DSOs) since they are responsible for the planning and operation of distribution networks and for resolving the problems caused by the change of end-users' habits. To identify and visualize pandemic-induced changes, an integrated geographic information system (GIS)-based tool is developed and presented in this paper. After identifying errors in GIS and end-users' consumption data and preprocessing them, pandapower and the developed harmonic calculation extension are used for the analysis of different power quality (PQ) indicators in low-voltage (LV) distribution networks. As a final step of the developed tool, the impact of COVID-19 on PQ indicators is visualized using GIS.

Keywords: COVID-19, end-users, geographic information systems, low-voltage network, power quality

1. INTRODUCTION

The end of 2019 was marked by the appearance of the new coronavirus disease (COVID-19). The novel disease changed the world as we know it and has caused the slowing and closing of the economy, industry, tourism, electricity, and many other business sectors. Several research papers consider the impact of COVID-19 on different aspects of power system planning and operation, e.g., electricity markets and market operations [1], CO_2 emissions [2], consumption of end-users [3], etc. Based on the measurements collected from the smart meters, the impact of COVID-19 on voltage magnitude, voltage unbalance, and total harmonic distortion (THD) is shown in this paper.

The challenges caused by the COVID-19 pandemic, and other changes in the distribution networks, e.g., an integration of distributed energy resources have put the focus on the need for the development of tools that can be used in the planning and operation of distribution networks. The fundamental idea behind these tools is based on the communication between different systems and databases which need to be integrated so that Distribution System Operators can use them in different network analyses.

One of the systems that is recognized as an important part of distribution networks operation is the Geographic Information System (GIS). Often, using GIS data is not possible without further processing and editing, needed to correct identified errors [4]. Since GIS is one of the many systems and tools used in the planning and operation processes, it is important to enable communication between different systems, databases, and tools [5].

Changes caused by the penetration of distributed energy resources (DERs) can cause several problems related to power quality (PQ). A high number of single-phase connected devices can lead to an unallowed voltage unbalance [6], which consequently causes increased technical losses in distribution systems [7]. DERs and home appliances are power electronic (PE)

Selection and peer-review under responsibility of the scientific committee of the 13_{th} Int. Conf. on Applied Energy (ICAE2021).

devices-interfaced, which impacts harmonic distortion in distribution networks. Therefore it is important to develop analyses tools, evaluate and potentially mitigate the increased distortion [8]. Some of the PQ-related problems, such as overvoltage or undervoltage can be mitigated by a joint operation of multiple DERs, e.g., PVs and EVs [9], [10]. In this paper, PQ parameters are analyzed by using pandapower [11] and a newly developed balanced and unbalanced harmonic analysis tool [12] developed by the authors of this paper.

Based on the literature review and identified research gaps, we propose the following contributions in this paper:

- Development of an open-source, highly automatized, GIS-based tool, that is used in the first step for editing and processing the data and removing the detected errors.
- A comprehensive analysis of PQ indicators in LV network. Analyses are made with data from before and during the COVID-19 pandemic. Therefore, the impact of COVID-19 on an LV network and anomalies caused by the pandemic are presented in this paper.
- After the simulations, the results are visualized using a GIS-based tool. The visualization of PQ indicators contributes to an easier assessment of the correlation between COVID-19 related anomalies and PQ indicators in LV residential networks.

2. METHODOLOGY

2.1 GIS data and the mathematical model of a network

Even though there are numerous advantages of GIS data, as mentioned before, often it cannot be used in the initial form. Also, not all data about distribution networks, e.g., end-users' consumption, is stored in one system or database. Therefore, it is necessary to develop an integrated tool with enabled communication between several systems and databases, that has the possibility of removing errors and prepare data for further analyses.

The tool presented in this paper is based on open-source technologies, and with combining features of QGIS, Python programming language, and PostgreSQL with the PostGIS extension, edits data and removes errors from an initial set of Croatian DSO's GIS data. The first step is the detection of errors and afterward, the developed integrated tool is used for further processing of data. Several errors in GIS data were detected:

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

After the detection of all errors, using the automatized process, the developed tool successfully removes all errors and prepares the data for further analyses. The flow chart that represents an integrated tool and represents all the steps is shown in Fig. 1.

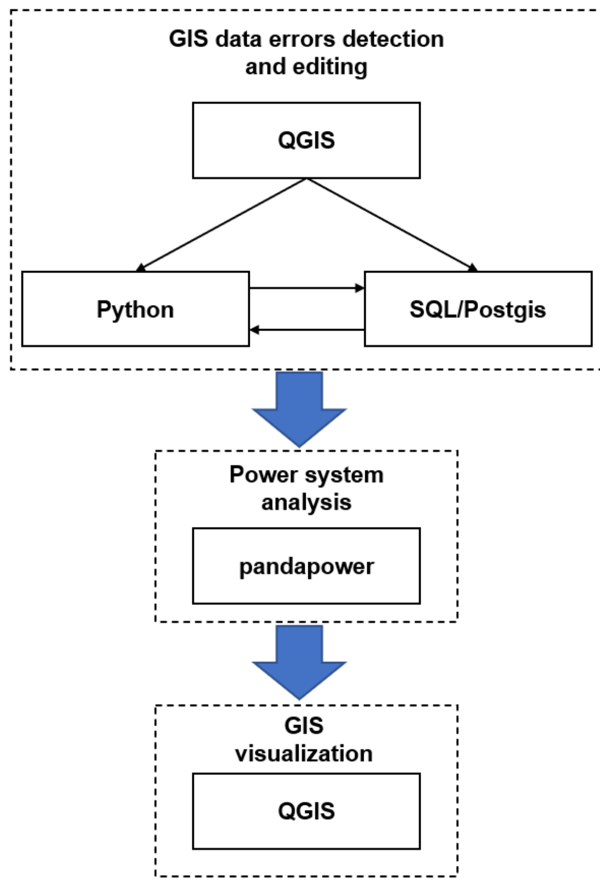

Fig. 1 Flow chart of the integrated tool

2.2 PQ analysis

In the first step of the PQ analysis, the open source, Python-based, pandapower library is used for the unbalanced load flow calculations. As a result of a calculation, phase voltage magnitudes and angles are calculated for each node. Based on the phase voltages and relation between phase and zero, negative, and positive sequence systems, voltage unbalance is calculated for each node in the observed network. As an upgrade of the pandapower library, a harmonic analysis tool is developed combining some of the already integrated functionalities and additions that allow full implementation of mathematical model briefly described with the following equations.

After the impedance matrix is calculated for a fundamental harmonic using already integrated pandapower functionalities, the phase impedance matrix $[Z_{abc,h}]$ for each higher-order harmonic h is calculated for a network consisting of elements that connect nodes k,l and that are impacted by non-fundamental frequencies defined with equation (1).

$$Z_{h,k,l} = R_{1,k,l} + jhX_{1,k,l} \tag{1}$$

As an input in the unbalanced harmonics calculation a harmonic current spectrum, determined as a percentage of fundamental harmonic current is defined for each load connected to a certain phase of a node. From the calculated harmonic impedance matrix and harmonic currents, a harmonic voltage drop vector is calculated with the equation (2).

$$[\Delta U_{abc,h}] = [Z_{abc,h}] \cdot [I_{abc,h}] \tag{2}$$

Since the voltage drop calculated with (2) is defined as a difference between the referent and all other nodes, it is necessary to calculate the voltage of the referent node. Same as for the calculation of the voltage drop, to calculate the voltage of the referent node, a phase impedance matrix of the referent node, i.e., of the external grid connected to the referent node, and a current that is being injected in the referent node must be determined. From the voltage of the referent node and the voltage drop vector, the voltage of each node in the observed network is calculated. The described procedure is conducted for each higher-order harmonic.

After the values of the harmonic voltages are determined for every higher-order frequency, it is possible to determine THD_n for every node n in the observed network (3).

$$THD_n = \sqrt{\sum_{h=2}^{H} \left(\frac{U_{n,h}}{U_1}\right)^2} \tag{3}$$

2.3 GIS visualization

After running simulations, the results obtained by pandapower are stored in a database. To analyze the impact of COVID-19 on LV networks, the QGIS tool was used to visualize the results of simulations. An analyzed network was visualized, where nodes are presented with various styles. Each of the styles can be matched with a value of an observed PQ indicator.

3. CASE STUDIES

An LV feeder used for an analysis in this paper is a real-world feeder with 66 nodes, 43 three-phase and single-phase connected users, and 64 lines.

Based on the government's regulations and considerations, two different time periods relevant to COVID-19 impact were defined. Both time periods are defined with real-world measurements of consumption, from which active and reactive power are calculated. The first period is defined as a pre-lockdown period, a period at the beginning of 2020, when there was no serious effect of COVID-19 and there were no restrictions. Second period is defined during a hard-lockdown period, when numerous sectors were closed, business was stopped, and most people spent the majority of their day at home.

Based on consumption measurements collected at 30-minute time intervals during two-week period, unbalanced load flow and harmonic calculation were made, and results of the simulations were used for comparison. The comparison was made using equation (4):

$$\frac{PQ_{ind\,hard} - PQ_{ind\,pre}}{PQ_{ind\,pre}} \cdot 100\% \tag{4}$$

where $PQ_{ind\,hard/pre}$ represents the value of the calculated PQ indicator (voltage magnitude, VUF, THD) both before and during the pandemic. The comparison was made using the average value calculated for each node, from values of PQ indicators for each period. After the values are compared, it is possible to determine how significant was a change of the value of a certain PQ indicator. After determining the impact of COVID-19 on PQ indicators in a residential distribution feeder, a GIS-based tool is used for visualization of the comparison.

4. RESULTS

A GIS visualization of the voltage magnitude change during the hard-lockdown is presented in Fig. 2. The results show that, compared to a pre-lockdown period, voltage magnitudes have decreased. However, the results show that the voltage magnitude in the lockdown period was not significantly lower compared to the pre-lockdown period. This can be explained by a fact that a hard-lockdown period came in the spring months when the consumption is generally lower than during the winter months, which is the pre-lockdown period. The differences would be more significant during the post-lockdown period that occurred during the summer months when a high number of HVAC devices used for cooling would lead to the increased voltage drop. Both before and during the lockdown, there are several periods in which voltage magnitude is lower than the limitation defined in European standards and national grid codes.

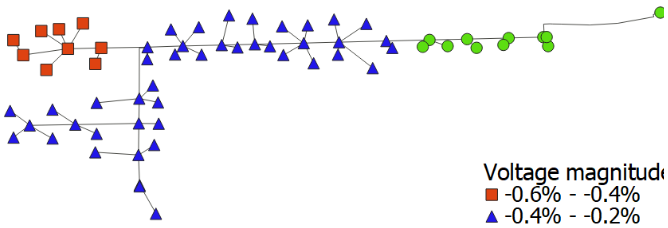

Fig. 2 Voltage change during hard-lockdown

The change of voltage unbalance factor in the lockdown period is visualized with Fig. 3.

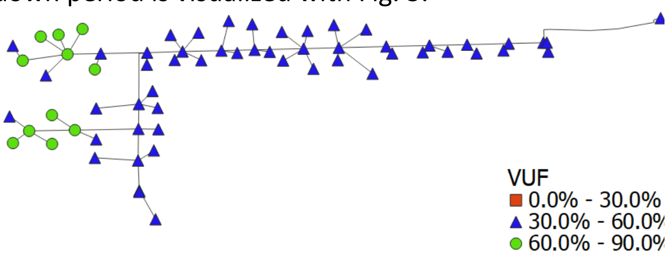

Fig. 3 VUF change during hard-lockdown

Unlike the voltage magnitudes, which decreased during the lockdown, VUF increased by more than 30%, and even for more than 60% at some nodes. The increase happened due to the increase in phase consumption that led to larger deviation between phase voltages. Such increase of voltage unbalance was expected only with the integration of single-phase connected DERs, especially when the connection phase is unknown [6]. The similar phenomena created only by the change of the end-users' behavior showed that the traditional planning and operation of distribution networks are not reliable during unexpected events. Also, the COVID-19 phenomena emphasize the need for the development of new tools and an approach in the planning of new, active distribution networks. Despite the increase, both in the pre-lockdown and hard-lockdown period, VUF values do not violate the limitations defined in European standards and national grid codes.

The impact of COVID-19 on the value of THD is shown in Fig. 4. With the exception of one node, the value of THD has increased in all other nodes during the hard-lockdown period. Similar to the case of analyzing voltage magnitudes, the change of the THD value is not so significant. The reason is that the characteristic of loads that are more used during winter are nonlinear and their contribution to the harmonic pollution is more significant. The increase is not as emphasized as in the case when VUF was observed, but it shows that further increase of power electronics' share can lead to potential problems related to harmonic distortion. Also, in some observed periods, COVID-19 restrictions caused a violation of limitations defined for THD.

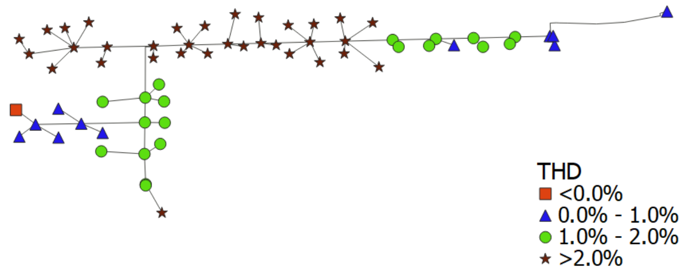

Fig. 4 THD change during hard-lockdown

5. CONCLUSION

In this paper, the impact of COVID-19 on PQ indicators in an LV residential feeder is being analyzed with an integrated tool based on the GIS technology and the open-source pandapower library. The tool is used for detection and removing errors in the initial GIS data set, unbalanced load flow and harmonic calculations, i.e., determining PQ indicators in an LV network, and a visualization of PQ indicators changes during the lockdown period.

The results show that the lockdown negatively affected all observed PQ indicators, i.e., voltage magnitude decreased, while VUF and THD increased. Even though the changes do not cause a significant problem in the operation of distribution networks, it shows the concerning trend of PQ distortion, which can be more emphasized with the uncontrolled installation of DERs. Due to increased consumption and a longer stay at home during the pandemic, it would be possible to exploit the end-users' potential and with different approaches, e.g., demand-side management or flexibility, solve PQ-related problems in LV networks.

Since after the first hard-lockdown period, there were several different periods in which there were no or few restrictions, e.g., a period of soft-lockdown, it would be beneficial to observe how the change of regulations affects different technical parameters in LV distribution networks. With the tool presented in this paper, it is possible to make analyses for other periods and also for other case studies, and not only for those defined by the COVID-19.

ACKNOWLEDGEMENT

The work is supported in part by Croatian Science Foundation (HRZZ) and Croatian Distribution System Operator (HEP ODS) under the project IMAGINE – Innovative Modelling and Laboratory Tested Solutions for Next Generation of Distribution Networks (PAR-2018-12) and in part by the European Structural and Investment Funds under project KK.01.2.1.02.0042 DINGO (Distribution Grid Optimization).

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