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The study of the impact of renewable energy sources generation on voltage losses in the distribution grid lines using the wavelet coherence

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Abstract: This paper proposes the use of wavelet coherence to conduct a study on the impact of renewable energy sources' generation on voltage losses in lines. The case study of the low-voltage distribution grid equipped with seven photovoltaic panels and one wind turbine was examined to demonstrate the functionality of the proposed methodology. Based on the simulation studies, the concept of how time-varying generation from the wind turbine or photovoltaic panels can affect the voltage losses in the selected power lines over one month was discussed. The analysis results were visualized using wavelet coherence delay plots. In contrast to other related studies, this research also includes additional plots like scale-averaged coherence, scale-averaged phase shift, time-averaged phase shift, and time-averaged coherence. The conducted studies extend and enrich the current view on the impact of renewable energy sources' generation on the power grid. The use of wavelet coherence can also help highlight additional information that may be ignored or overlooked, especially in fast-paced systems. This kind of research may be useful for supplementing the results of load flow calculations with additional information on the voltage losses for distribution grid operators. It can be considered a general tool for conducting a more in-depth analysis of the influence of renewable energy sources on the power grid.

Key words: continuous wavelet transform, distribution grid, renewable energy sources, voltage losses, wavelet coherence

1. Introduction

In recent years, progressively renewable energy sources (RESs) have been installed in low-voltage distribution networks [1, 2]. Wind turbines and photovoltaic panels (PVs) are among the most popular RESs. The presence of these sources affects not only the amount of electricity but also, among other factors, the value of the voltage losses. Energy generation from RESs depends on the weather conditions in the given area. Therefore, the varied values of generated power may impact the values of voltage losses in the network. Distribution networks play a crucial role in

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power delivery and usually supply many end users of electricity. Moreover, the voltage value changes quite often, assuming that these variations are within the permissible range.

The wavelet transform (WT) is one of the best and most popular tools for performing the analysis of the variable time series (especially, nonstationary ones). This transform may be performed as a discrete wavelet transform (DWT) or a continuous wavelet transform (CWT). When using the CWT, the wavelet coherence (WC) can be applied. This computation is useful for studying the impact of one time series on another one and their co-movements over time or frequency. The final WC calculations can be presented as coloured plots called scalograms.

Based on the above discussion, there is a justified necessity to apply the wavelet coherence to perform the analysis of the possible interactions between the selected electrical parameters, such as nonstationary time series of active power generation and voltage. The purpose of this paper is to present the study of the impact of renewable energy sources generation on the voltage losses values in the distribution grid lines using the wavelet coherence. Thanks to the use of the wavelet coherence, it is possible to visualize the relationships regarding voltage losses that cannot be easily obtained by calculating traditional load flows. The author's objective is to highlight the features of this application and to indicate that it can be easily used for similar and further studies in this field.

This paper is organized as follows. The first part presents the related work review. Next, the materials and methods used are described. The main part is devoted to the results of the wavelet coherence delay plot analysis for the examined example distribution network. The final part summarizes this study and focuses on the main conclusions.

2. Related work review

The comprehensive literature review was conducted to collect and summarize the current knowledge on the impact of the RES on voltage, as well as wavelet transform usage. This part reviews the previous work related to the paper topic and outlines the study gaps that can be addressed in the presented approach. The operation of renewable energy sources is still an important topic. This is evidenced by the recently published considerable number of research papers that deal with this subject, for example [3]. In addition, the wavelet analysis is gaining growing recognition in the many fields of electrical power engineering, for example [4]. Due to the large scope of the examined topic, the presented review of related work focuses only on the issues such as the impact of the RES on voltage, the use of the wavelet transform to analyse the operation of the RES and voltage values.

In the available literature there are some recently published articles related to the topic of the influence of renewable energy sources on the voltage values. The authors of [5] performed the simulation studies on the impact of RESs on the variability of the effective value of the distribution network voltage using the OpenDSS software. Work [6] explores the influence of RESs along with the storage devices on electric energy losses and voltage terms in a medium voltage network. Paper [7] focuses on improving voltage deviation and minimizing active losses

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in transmission lines for a network with the RES. In paper [8], the authors indicated that selecting the appropriate location and capacity of distributed generation can reduce the network losses successfully. The authors of [9] suggest using of the genetic algorithm and particle swarm optimization to minimize the annual energy losses and voltage deviation of the distribution grid with wind turbines and PV panels. Work [10] presents the impact of hybrid distribution power sources on voltage, power losses, and electricity costs in the IEEE-13 bus test system. Paper [11] describes the impact assessment of PV and wind energy integration on a low-voltage distribution network in Tunisia. Work [12] deals with the impact of PV installations on changes in voltage levels in the low voltage network. The voltage rise phenomenon caused by a high concentration of renewable distributed generators was the topic of work [13]. Research [14] deals with the algorithm for estimating the impact of RESs on voltage fluctuations in the medium voltage network. Work [15] focuses on the interaction between RESs and loads regarding the voltage characteristics. Paper [16] indicates that RESs are introducing significant challenges for distribution system management, particularly at the low-voltage level. Moreover, that work also deals with the usage of the Monte Carlo method. The authors of [17] have drawn attention to the fact that voltage regulation in low-voltage distribution networks is becoming increasingly complex due to the growing penetration of renewable energy sources, as well as electric vehicles. The authors of [18] propose a model predictive control-based corrective control framework designed to manage voltage stability and congestion in distribution systems with the RES. Paper [19] proposes a method for causes identification and sources localization of multistage voltage sags under the influence of high penetration of renewable energy sources. The author of [20] was focused on examining the relationship that may exist between voltage fluctuations in electricity transmission networks and the variation in photovoltaic system production. Work [21] deals with voltage sensitivity of various nodes and evaluates the impact of power level changes in PV access nodes at different locations on the voltage at a target node, particularly when the voltage exceeds acceptable limits. Paper [22] investigates the power quality issues arising from the grid integration of low-voltage distributed PV systems, such as reverse heavy overload and voltage over-limit conditions. The authors of [23] propose a two-tier active voltage control strategy tailored for coordinated wind-PV grid integration. Paper [24] demonstrates the studies on the influence of different penetration rates of distributed photovoltaic power supply on the voltage of a typical rural distribution network with distributed photovoltaic power. Work [25] investigates the impact of different photovoltaic access scenarios on the voltage and network losses of a distribution network. Paper [26] investigates the use of battery energy storage systems in combination with a photovoltaic generating system to improve voltage management in a distribution system with voltage-dependent loads. The authors of [27] are proposing an integrated optimization framework for active power supply in a radial, distribution-like network through the optimal siting and sizing of photovoltaic units and wind turbines, combined with a real-time pricing based demand-side response program. The problem is addressing, among others, also voltage drops. Work [28] describes a method for improving power grid voltage profiles by more effectively regulating reactive power through the integration of hybrid renewable energy systems into smart grids. The authors of [29] are presenting a new approach

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for quickly and accurately detecting topology attacks in electric power systems. This resolution aims to minimize losses and restore critical loads while also including PV system generation.

Another group of papers is devoted to the usage of the wavelet transform to investigate the operation of renewable energy sources. Paper [30] explores the method of analysing PV system performance signals with the wavelet transform, robust regression as well as extreme point analysis. In article [31], the author uses the wavelet approach to examine the relationship between the carbon dioxide emissions and renewable energy consumption. Work [32] presents the use of the wavelet analysis to detect the islanding of a single-phase grid connected PV system. Research [33] proves (using Morlet wavelet and wavelet coherence analysis) that the operation of the residential solar energy has a significant effect on mitigating the CO_2 emissions. The authors of [34] use the wavelets to analyse the variability of aggregated photovoltaic systems. Paper [35] focuses on fault diagnosis of wind turbine blades using the continuous wavelet transform based on the deep learning model with a vibration signal. Work [36] shows the wavelet-based normalized flow for anomaly detection in photovoltaic electroluminescence with nonstationary textures. Paper [37] deals with the impact of distributed generator penetration levels on the voltage profile and the power losses in the radial low voltage network. The authors of [38] show how to evaluate the influence of the RES on voltage and reactive power by using of the combinational evaluation method. Paper [39] proposes a wavelet-based multiscale coupling index for transient voltage stability assessment in high-renewable grids.

The last part of related papers is devoted to the usage of the wavelet transform to perform voltage value analysis. Article [40] explains the wavelet packet evaluation to improve the detection of voltage sags. Paper [41] explores the idea of voltage interruption signal using the continuous, discrete, and packet wavelet analysis. Work [42] focuses on applying the wavelet thresholding method to process voltage sags, rises and interruption signals containing noise. The authors of [43] present the selection of the wavelet generating function in voltage interruption detection. Work [44] shows the evaluation of power quality disturbances in a PV-connected IEEE-14 bus test system using the lifting-based wavelet transform and random forests. Paper [45] presents lifting scheme-based match wavelet design for effective characterization of different types of voltage sags. Work [46] was devoted to the automatic identification of voltage sag events using matched wavelets and classifier ensembles. The authors of [47] and [48] used wavelet transforms to investigate voltage sags. Work [49] proposed a wavelet transform-based multiscale analysis method for achieving multifunctional integration of multi-objective collaborative voltage estimation in distribution networks. Paper [50] presents accurately detecting voltage swell disturbances by using wavelet vanishing moments. The authors of [51] were using wavelet packet transform for the research on power measurement algorithm for voltage sag.

The numerous and different studies have been developed and presented on the topics of the operation of renewable energy sources and the usage of the wavelet transform. Although many interesting topics were uncovered, these papers still do not focus directly on the application of the wavelet coherence (also with additional plots), particularly for the values of the voltage losses in the distribution grid during energy generation from the RES.

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This research has been motivated by the desire to overcome the limitations of the above-mentioned approaches, including the inability to use the wavelet coherence (along with additional plots) for a more in-depth analysis of RES generation and their influence on other parameters. At the same time, this research has been conducted to show how dynamic relationships between two different time-varying variables can be captured and presented graphically. Applying the wavelet transform analysis for renewable energy sources and their impact on the power grid is still not fully recognized or described.

The topic of renewable energy sources' impact on the power grid is very broad. This study focuses only on the influence of PV panels and wind turbine active power generation on the voltage loss values in the power lines of the distribution network.

The novelty of this study is the use of wavelet coherence to perform an analysis of RES influence on voltage losses. The existing technique (wavelet coherence analysis) was augmented with additional plots and applied to conduct a more in-depth analysis. Consequently, the proposed method produced new graphical results, which can help to better understand how PV panels or wind turbine generation can affect voltage losses in lines. Unlike previous studies, this paper demonstrates that wavelet coherence can be successfully used for the examination of the co-movement of nonstationary time series, like active power generation and voltage losses.

This paper attempts to fill in the study gaps by introducing the research objective to establish a suitable and straightforward model for the future analysis. The main contributions of this paper are:

1) the use of the wavelet coherence to study the impact of the RES generation on the voltage losses in the lines of the distribution network;
2) to show the plots of scale-averaged coherence, scale-averaged phase shift, time-averaged phase shift and time-averaged coherence in addition to the standard wavelet scalogram – these were applied to perform a more in-depth coherence analysis;
3) to fill in the study gaps in the topic of RES operation using the wavelet coherence.

3. Materials and methods

3.1. Introduction

The study was divided into two parts:

1) the simulation of the renewable energy sources operation in the example low voltage distribution network and
2) the use of the wavelet coherence plots to analyse the selected waveforms obtained from the simulation.

In the first part of the research, the detailed time series were obtained from the specialized simulation software. The obtained data show the variability of the generated active power and the percentage values of voltage losses in the lines. Then, using the wavelet analysis with the dedicated software, the impact of renewable energy sources generation on voltage losses was

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investigated. Finally, the analysis results were presented in the form of extensive graphics, enabling their interpretation and evaluation.

3.2. Simulation of renewable energy sources operation in the example low voltage distribution network

The OpenModelica software [52] with Buildings library [53] was used to simulate the operation of the distribution network containing renewable energy sources. OpenModelica is a popular and long-established environment used for modeling and simulating dynamic systems, including also electrical power systems. The program can be complemented by various libraries. It was decided to use the Buildings library because the examined network model from that package contained the extensive data regarding the weather conditions, PV panels and wind turbine conditions and parameters, power lines properties and final load values and their properties. In general, that library is dedicated to building energy and control systems modeling.

In the energy transmission path, the current I causes a voltage loss across the resistance R in phase with the current, and on the inductive reactance X, it causes a voltage loss leading the current by 1/4 period. According to Kirchhoff's second law, the voltage at the beginning of the circuit is balanced by the sum of the voltage at the end of the circuit and both voltage losses. Voltage loss is described as the difference of complex numbers - the voltage at the beginning of the line and the voltage at the end of the line, while voltage drop is described as the difference of voltage magnitudes at the beginning of the line and at the end of the line.

Voltage drops are used and calculated more often because they are easier to determine than the full value of voltage losses. In practical calculations, it is usually assumed that the voltage drop is equal only to the longitudinal component of the voltage loss. However, the omitted part of the voltage loss value is related to the presence of reactive power. Hence, it should be considered (even in the medium and low voltage lines with smaller reactance) in case of the growing number of final electricity loads having lower power factor (cos φ) values.

The voltage drop value comes from simplified voltage loss calculations. Therefore, to accurately present the impact of renewable energy sources on voltage conditions, it was decided to use more precise voltage loss values. It is desirable to use precise nonstationary time series for wavelet coherence analysis. The more accurate the waveforms, the more detailed the coherence results and the more insightful conclusions from the analysis of the impact of one signal on another.

Figure 1 presents an example of the low-voltage distribution grid (a part of the Buildings library). The grid consists of an external power system (EPS), 8 power lines, 7 loads, 7 PV panels and one wind turbine.

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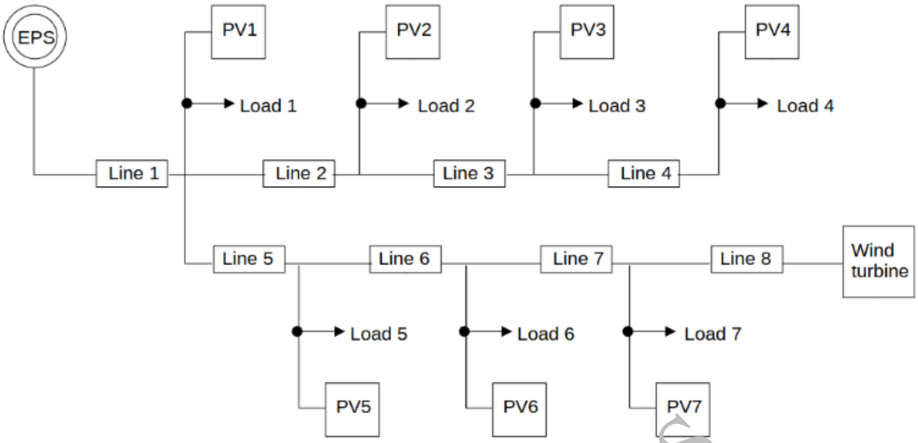

Fig. 1. The example of the low voltage distribution grid with RES. The author's work based on [53]

Because OpenModelica is the time-domain analysis software, the total simulation period was set to 2 678 400 seconds, which is equal to 31 days (one month). Hence, it was possible to obtain the detailed time series corresponding to the longer period, while parameters such as active power generation from RESs changed due to various weather factors. The number of time intervals was set to 744. OpenModelica transforms a given model into an ODE (ordinary differential equation) representation by using numerical integration methods. In the presented study, an implicit, higher-order, multi-step solver with step-size control was used (called DASSL). During a simulation, the tolerance was set to 1e-06. The total simulation time was around 30 seconds.

Due to the large number of the obtained results, only the selected ones (PV2 and wind turbine active power generation, line 2 and line 7 percentage voltage losses) were considered during the presented study. The selected parameters of lines and renewable energy sources are shown in Tables 1–3.

Table 1. Selected line parameters. Based on [53]

Parameter name	**Symbol**	**Value**	**Unit**
Length	l	300	m
Resistance	R	0.543	Ω
Nominal voltage	U_n	480	V

Table 2. Selected PV2 parameters. Based on [53]

Parameter name	**Symbol**	**Value**	**Unit**
Gross surface area	A	38.12	m^2

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Efficiency of DC/AC conversion	η	0.89	[-]
Nominal voltage	U_n	480	V

Table 3. Selected wind turbine parameters. Based on [53].

Parameter name	**Symbol**	**Value**	**Unit**
Heigh over ground	h	15	m
Efficiency of DC/AC conversion	η	0.92	[-]
Nominal voltage	U_n	480	V

Below are four examples of the waveforms of active power generation from PV2 (Fig. 2), wind turbine (Fig. 3), percentage voltage losses in lines 2 and 7 (Fig. 4 and Fig. 5). The *x*-axis represents the days, while the *y*-axis shows active power in watts (Fig. 2 and Fig. 3) or percentage voltage losses (Fig. 4 and Fig. 5) on the *y*-axis, respectively.

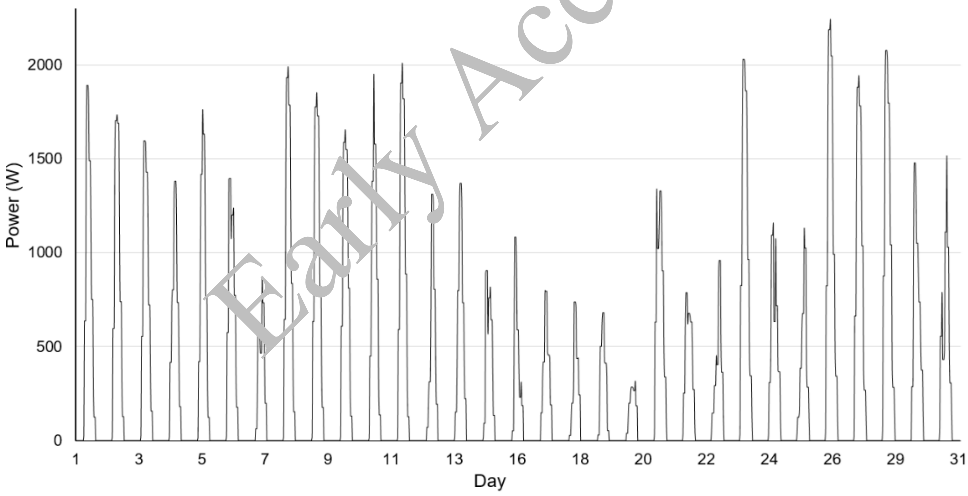

Fig. 2. Photovoltaic Panel 2 (PV2) active power generation. The author's own work based on [53]

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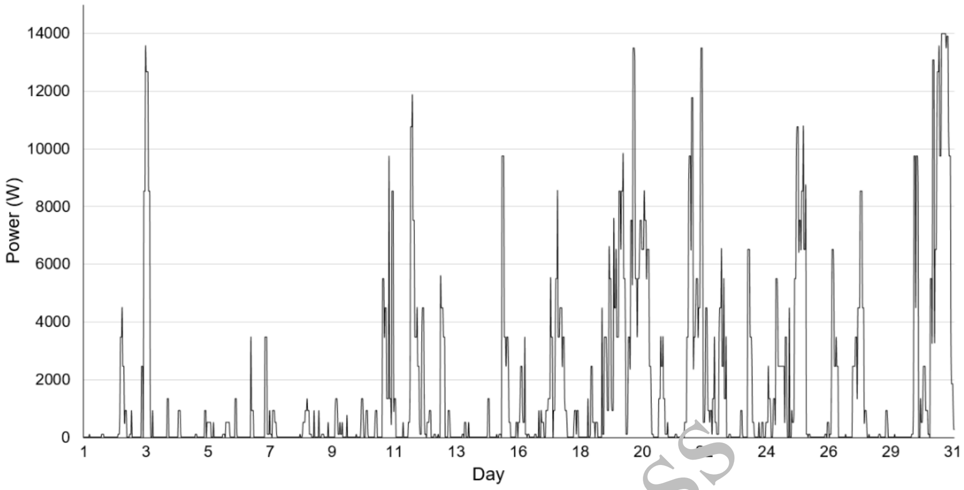

Fig. 3. Wind turbine active power generation. The author's work based on [53]

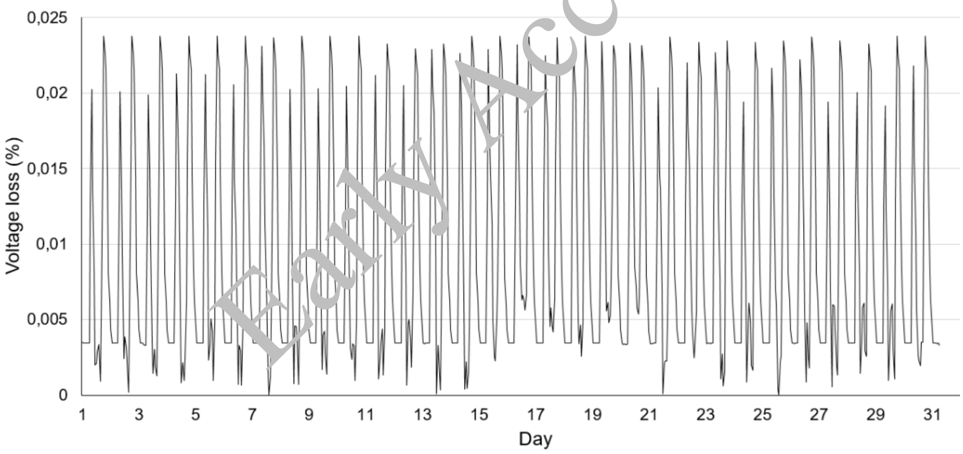

Fig. 4. Line 2 percentage voltage losses. The author's work based on [53]

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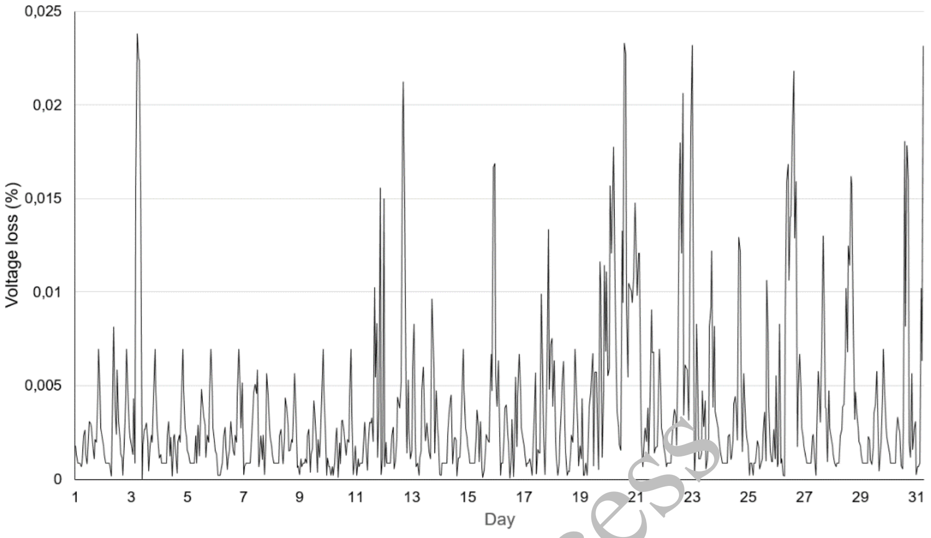

Fig. 5. Line 7 percentage voltage losses. The author's work based on [53]

As can be seen, all the above-mentioned time series are nonstationary – their statistical properties change over time. In addition, each of them changes rhythmically with other related parameters. In the case of the PV panels, the output generation is strongly dependent on weather factors such as temperature, solar irradiance and time of day. In the case of the wind turbine, the output generation is dependent on wind speed and wind direction, or atmospheric pressure. All RES outputs are also connected to their exact location in the grid. It is worth emphasizing that the wind turbine (due to its stochastic nature) can significantly affect the voltage loss profile (Fig. 5). The final voltage loss values are mainly influenced by the length of the lines and active power loads. Both RESs have intermittent power generation, resulting in fluctuations in the power grid. Due to their properties, all the time series obtained from the mentioned simulation are suitable for further wavelet analysis.

3.3. Continous wavelet transform

In general, a signal is an observation (for example – a record) of a series of events resulting from a certain process. For many years, the Fourier transform had been one of the main tools for signal analysis. As a result, the examined process could be represented in the frequency- domain. Hence, either only the time-domain information or only the frequency domain information could be viewed. If the analysed signal was stationary, this drawback was not significant for the further analysis. The wavelet transform can be introduced to overcome the mentioned limitations.

It must be emphasized that the electrical power grid, particularly the one equipped with renewable energy sources, operates as a fast-paced system. Hence, many measured time series are nonstationary ones (for example – Figs. 2–5). The wavelet transform is widely used for further analysis of nonstationary signals. It is very convenient for examining especially

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periodicities and trends. In general, the name “wavelet” refers to the similarity of the applied functions to the traditional waves in nature. The basic properties of wavelet functions are finite signal power, a mean value equal to zero and finite bandwidth. Wavelets are the equivalents of the sine and cosine trigonometric functions, but unlike them, they are irregular.

Using the wavelet transform, it is possible to analyse a given signal by looking for its similarity to shifted and scaled versions of the original wavelet, called the mother wavelet. The CWT for the time series with equal intervals can be expressed by Eq. (1). This equation is the convolution of the time series under study with the scaled and shifted mother wavelet function.

$$W_m(s) = \frac{\sigma_t}{\sqrt{s}} \sum_{n=0}^{N-1} x_n \varphi * \left[\frac{(n-m)\sigma_t}{s}\right], \tag{1}$$

where: σ_t is the equal interval between signal samples, s is the scale factor, N is the number of the samples of the observed time series, x_n is the n-th element of time series (where n = 1, 2, 3,…, N), φ is the wavelet function, m is the shift factor, and $*$ is the conjugation of complex numbers.

In Eq. (1) the scale factor s describes the influence on wavelet time duration, while the shift factor m is responsible for changing the position of the wavelet function on the time axis. Both values of s and m define the rate of similarity of the chosen mother wavelet function to the examined time series. Small values of scales are used for performing analysis of dynamic signal details (the mother wavelet is “compressed” at high frequencies), while large scale values are used for analysing the slowly changing parts (the mother wavelet is “stretched” at low frequencies).

The Morlet wavelet is one of the most popular mother wavelet functions. This function is described by Eq. (2). The shape of this wavelet (real part only) is presented in Fig. 6.

$$\psi_\sigma(t) = c_\sigma \pi^{-\frac{1}{4}} e^{-\frac{1}{2}t^2} \left(e^{i\sigma t} - \kappa_\sigma\right), \tag{2}$$

where: κ_σ is the admissibility criterion described by Eq. (3), σ is the resolution related factor, and c_σ is the normalisation constant described by Eq. (4).

$$\kappa_\sigma = e^{-\frac{1}{2}\sigma^2}, \tag{3}$$

$$c_\sigma = \left(1 + e^{-\sigma^2} - 2e^{-\frac{3}{4}\sigma^2}\right)^{-\frac{1}{2}}. \tag{4}$$

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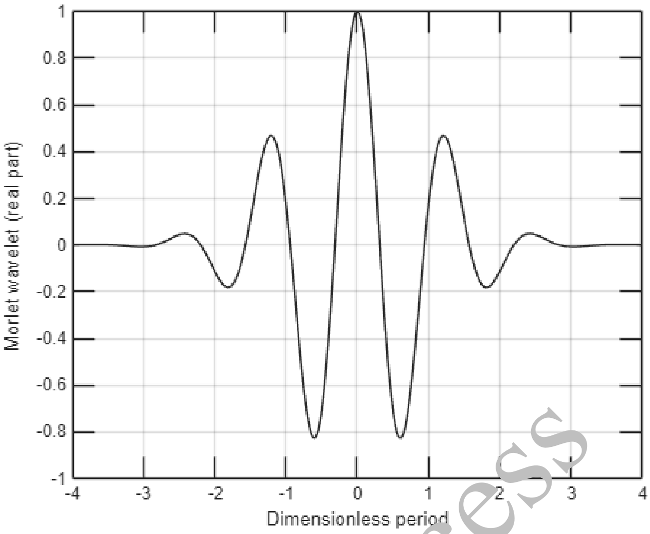

Fig. 6. Morlet wavelet shape (real part only)

In the presented study, the Morlet wavelet was used as the mother wavelet function. The motivation to adopt this function was its similarity to typical shapes in the examined time series. Moreover, the Morlet wavelet function usually offers good time-frequency localization, which is especially desired during coherence analysis. In general, the CWT computation process can be described in five steps:

1) choose the mother wavelet function whose shape most closely resembles the shapes of the examined time series, for example the Morlet wavelet,
2) “place” the mother wavelet function at the starting point of the tested signal,
3) establish the similarity between the mother wavelet function and a part of the signal,
4) “shift” the wavelet function in time and redo similarity calculation for the ongoing time series part,
5) “stretch” the wavelet function and repeat the preceding steps until all scales are finished.

3.4. Wavelet coherence

The cross-wavelet transform (XWT) can be constructed by performing the CWT on two signals. The XWT of two signals is described by Eq. (5).

$$W_n^{XY} = W_n^X W_n^{Y*}, \tag{5}$$

where: W_n^{XY} is the cross-wavelet transform (XWT), W_n^X and W_n^{Y*} are the continuous wavelet transforms of the X and Y signals expressed as a convolution of the n-th element of the signals with the normalized and scaled mother wavelet function, and * is the conjugation of complex numbers

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One of the major advantages of the XWT is the possibility to expose the common power and relative phase using the time-frequency domain. Finally, the wavelet coherence can be introduced. WC is described as the measure between two CWTs, which can show the potential interrelationships between two considered signals. The WC of two waveforms is given by Eq. (6).

$$R_n^2(s) = \frac{\left|S(s^{-1}W_n^{XY}(s))\right|^2}{S(s^{-1}\left|W_n^X(s)^2\right|)\cdot S(s^{-1}\left|W_n^Y(s)\right|^2)}, \tag{6}$$

where: $R_n^2(s)$ is the coherence factor, S is the smooth operator, s is the scale factor, W_n^X and W_n^Y are the continuous wavelet transforms of the time series expressed by a convolution of the n-th sample from the signal with normalized and scaled wavelet, and W_n^{XY} is the cross-wavelet transform of x_n and y_n samples.

In general, WC computation process can be described in five steps:

1) provide two examined time series with the same number of samples,
2) calculate the continuous wavelet transform,
3) calculate the cross-wavelet transform,
4) determine statistical significance by applying the Monte-Carlo approach,
5) perform results interpretation by analysing the graphical outputs of WC.

As a result of applying the wavelet coherence, it is possible to find the strength of the correlation and the phase shift (delay) between the examined signals in the time-frequency domain. The available range of coherence varies between 0 (extremely low coherence) and 1 (extremely high coherence). The phase shift can be calculated by using a phase angle shift function for complex numbers of the cross-wavelet spectrum. Lastly, radians are converted to the expected time resolution.

The interpretation of the obtained results is simple and intuitive. The level of coherence is illustrated graphically by the appropriate colour. Depending on the colour map used, the areas of high coherence may be marked with a light colour (for example, yellow in Fig. 7), whereas weak parts can be indicated with a dark colour. By looking at the axes, time periods with oscillations (on the vertical axis) and times of occurrence (on the horizontal axis) can be distinguished.

During WC analysis, the first examined signal is called the basic one, while the other is referred to as the second one. In the final plots, the arrows and their directions describe the phase interaction between both signals. The phase shift can be positive (the second signal lags the basic signal, right-aligned arrows) or negative (the basic signal lags behind the second signal, left-aligned arrows). This information can be useful to determine which signal controls the other. In the case of a positive lag the basic signal controls the second signal, while a negative lag indicates the opposite situation. Further and more detailed information on the basics of the CWT, XWT and the wavelet coherence, as well as more advanced topics, can be found in [54, 55].

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3.5. Using the specialized software for the wavelet analysis

The study of the impact of RES generation on the voltage losses in distribution networks was a multi-stage task. To perform the main analysis, the specialized software was used. The detailed simulation results from OpenModelica and the Buildings library were exported to separate files. Then, the data was imported into the MATLAB environment, which is well recognized in many fields, especially signal processing. In the case of the MATLAB part, the typical time for obtaining the final results was a few seconds. During wavelet coherence calculations, the Monte Carlo method was used for estimating the statistical significance level. Wavelet coherence statistical significance identifies regions in the time-frequency plane where two signals are significantly correlated. Viewing data from various perspectives often involves transformations such as the continuous wavelet transform and wavelet coherence. Monte Carlo methods have also been used to study random processes, such as renewable energy sources' active power generation.

The complete wavelet transform calculations were made and visualized using MATLAB supplemented by a dedicated script called Coherence-delay Map Plotter [56].

4. The results of the wavelet coherence analysis

The presented study will focus only on the correlation and phase delay between two pairs of signals. The first pair is the active power generation from Photovoltaic Panel 2 (PV2) and percentage voltage losses in line 2 (Fig. 4). The second pair is the active power generation from the wind turbine and percentage voltage losses in line 7 (Fig. 5). The wavelet coherence analysis results are shown in two figures (Fig. 7 and Fig. 8). Each of them contains panel (a), a coherence-delay map; panel (b), scale-averaged coherence; panel (c), scale-averaged phase shift, and panel (d), time-averaged coherence.

The coherence-delay map is the main graphic result of the wavelet coherence calculations. This graph shows the correlation between two waveforms in the time-period domain. Thanks to different period sizes (on the *y*-axis), the studied phenomenon can be observed in both the short and long term. The proper colour map used [57] allows for easy differentiation of coherence values in the time-period domain. The areas of high coherence (0.8 and more) are marked in yellow, while the areas with low coherence (0.2 and less) are marked in dark blue and black. In addition, the varying shades of colours allow the degree of coherence to be distinguished. The neutral coherence values (0.5) are marked in pink. The scale-averaged coherence plot shows how overall coherence changes during the analysed period.

The scale-averaged phase shift plot is used to perform phase difference analysis of the two signals as a function of the time considered. Moreover, this plot can also show a lag (positive or negative) between the base and the second time series.

The time-averaged phase shift plot presents how phase shift and lag change as a function of the periods.

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The time-averaged coherence plot is the last plot. This graph shows the changes in time-averaged coherence as a function of scales.

In the above-mentioned plots, the phase shift indicates the difference in the pace of two subsequent maximum values, while the lag presents the variance in the pace of two succeeding attributes (minimum or maximum) of the examined time series.

In the presented study, the base signal was from the renewable energy source (PV or wind turbine generation, respectively) and the second signal was from the distribution power grid (percentage voltage loss in the selected power line).

In the case of PV generation analysis, the main coherence results are shown in panel (a) in Fig. 7 (coherence delay map). The *x*-axis shows days, and on the *y*-axis, there are periods expressed in hours. The bright yellow parts indicate extraordinarily strong coherence (0.9 or higher) between PV2 generation and the percentage voltage losses in line 2. The high coherence, however, does not occur for the entire considered period (31 days) but for most of the month. It is clearly visible that this coherence weakens around a 32-hour period on the 20th day and approximately a 16-hour period on the 8th, 24th and 27th days. In short periods (4-hour periods), the coherence was extremely high, but only on the days with the highest PV2 generation.

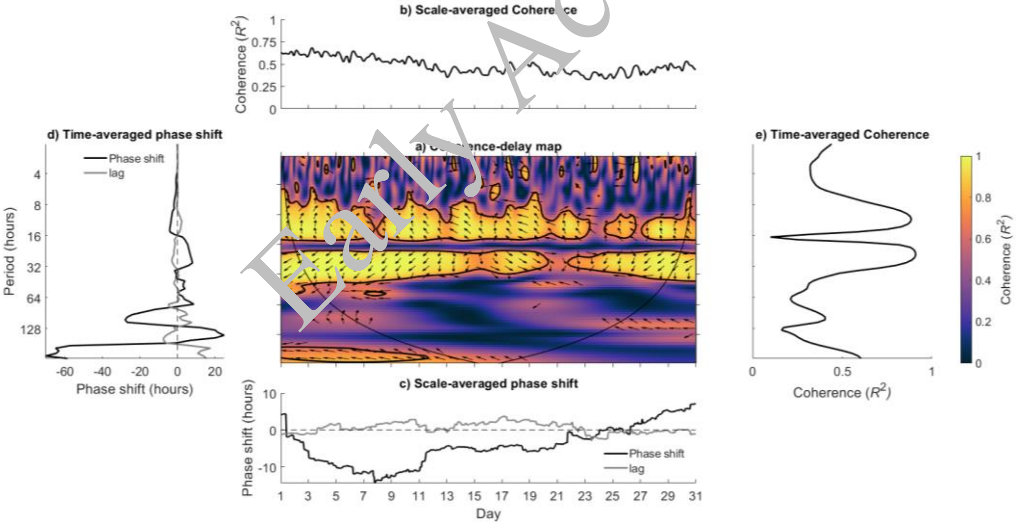

Fig. 7. Wavelet coherence plots for PV2 active power generation and line 2 percentage voltage losses

During the high coherence and the period of approximately 8 to 16 hours, the arrows were directed vertically upward (PV generation is in phase ahead of percentage voltage losses) or upward and slightly to the left. Both signals were out of phase with each other; voltage losses were leading PV generation, approximately on the 13th to 15th day and the 19th to 20th day.

For approximately 32 hours, the coherence was high except around days 20 and 21, which is reflected in the PV2 generation profile (Fig. 2). Most of the time, the arrows pointed down and

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to the left. Both signals were out of phase, and the percentage voltage losses lagged behind PV2 generation.

Panel (b) in Fig. 7 shows the scale-averaged coherence between PV2 generation and percentage voltage losses in line 2. The presented parameter oscillates between the values of 0.7 and 0.4 and is unstable. Moreover, it shows a decreasing trend over time until the end of the month.

Panel (c) in Fig. 7 represents the scale-averaged phase shift. The phase shift (the black line) is smallest on day 8 and then increases continuously over a period of about 8–16 hours on day 8 as reflected in panel (a). The positive lag values (the grey line) most of the time indicate a small influence of the PV generation on the percentage voltage losses.

Panel (d) in Fig. 7 shows the time-averaged phase shift. For most of the considered time, the phase shift is small and oscillates around 0 hours. The increase in lag and phase shift can be observed when the period cycles increase. The lag shows a smaller increase compared to the phase shift.

Panel (e) in Fig. 7 shows the time-averaged coherence. The presented parameter reaches the highest values (around 1) for periods from approximately 10 to 32 hours. The lowest values are for around 16 hours. The longer the considered period, the smaller the coherence.

In the case of wind turbine generation analysis, the main coherence results are shown in panel (a) in Fig. 8 (coherence-delay map). Unlike PV generation, the arrows mostly point straight and up to the right. As a result, wind turbine active power generation and line 7 percentage voltage losses are in phase (positively related). The areas of strong coherence occur for the longer periods (32-hour period and longer). Over time, the size of the coherence areas increases (which is reflected by the generation profile from Fig. 3). For short periods (4–8 hours), there are also more frequent and longer-lasting coherences.

Panel (b) in Fig. 8 shows the scale-averaged coherence between wind turbine generation and percentage voltage losses in line 7. The presented parameter oscillates between the values of 0.50 and 0.75 and is unstable. Contrary to the PV generation, it does not show any decreasing trend over time. A higher value of active power generated from a wind turbine than from a PV panel (Fig. 2 and Fig. 3) and longer periods of the wind speed required for power generation than the availability of solar power may be the reason for this phenomenon.

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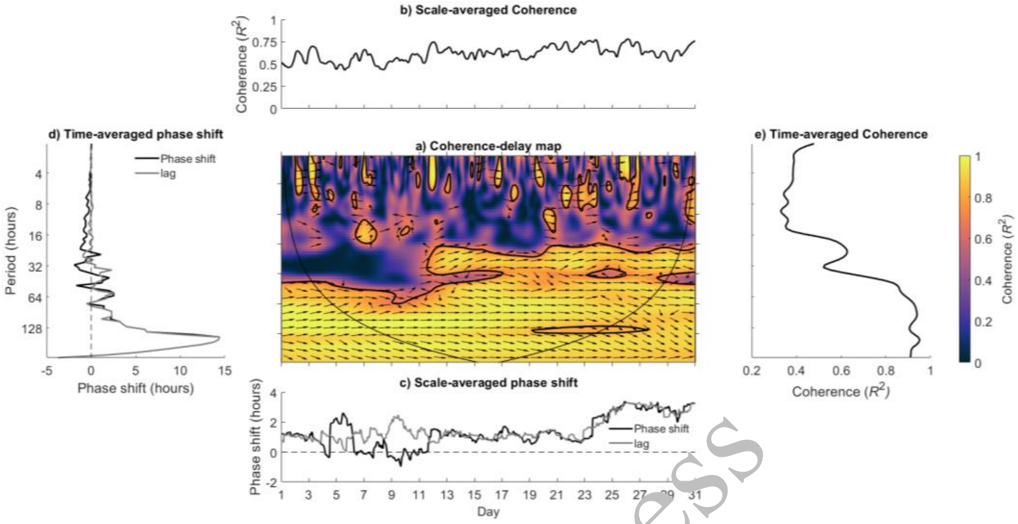

Fig. 8. Wavelet coherence plots for wind turbine active power generation and line 7 percentage voltage losses

Panel (c) in Fig. 8 represents the scale-averaged phase shift. During the entire examined period, the lag was always positive (above zero). This means that power generation from the wind turbine moderately affects the percentage voltage losses in line 7. The phase shift (the black line) reaches the negative values only around the 5th, 7th, and 9th to 11th days, which is also reflected in the generation profile in Fig. 3.

Panel (d) in Fig. 8. displays the time-averaged phase shift. Similarly to the previous case, the phase shift is small and oscillates around zero for most of the considered time. However, the increase in lag and a phase shift can still be observed during periods when cycles increase, but for smaller ranges compared to the PV generation. Panel (e) in Fig. 8 shows the time-averaged coherence. The presented waveform is more stable than the previous one for PV generation. Moreover, the longer the period (hours), the stronger the coherence.

5. Conclusions

The objective of this paper was to present the application of wavelet coherence to study the impact of renewable energy source generation on voltage losses in the distribution power network lines.

The collected coherence plots lead to the conclusion that the quality of the results presentation is particularly good. Hence, the application of the wavelet coherence to examine RES influence on the selected power grid parameters has proven to be a suitable solution. Moreover, both short- and long-term time and phase relationships can be easily captured. This is an undeniable advantage of applying wavelet coherence plots and is particularly important for studies of rapidly

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changing processes. The use of an appropriate group of colours (along with their shades) allows for smoothly varying coherences to be marked easily and further interpret graphically.

The usage of voltage loss waveforms instead of, for example, the total harmonic distortion (THD), was chosen due to the possibility of showing graphically that the value of voltage loss also indirectly depends on the weather conditions for renewable energy sources (like the wind turbine - Fig. 5). Such an impact could be overlooked by using only THD values. Voltage loss values can be used to assess the condition of existing or planned power networks. This is particularly important in low-voltage distribution networks, where renewable energy sources are increasingly located close to many electricity consumers.

The potential limitations of the presented methodology may be the availability of the input nonstationary time series (from simulation or real-world measurements) and the sufficient quality of this data to achieve acceptable wavelet coherence delay plots.

It needs to be emphasized that the obtained wavelet coherence outcomes depend, to a large extent, on the type of renewable energy source (PV panel or wind turbine) and the exact location of this source in the distribution network. Regardless of the generation type, the (d) type panel plots with the time-averaged phase shift should be considered over shorter time periods (for example, 8–32 hours only) due to the unstable and quickly changing active power output. For both RESs, the longer the analysis period, the higher the coherence value. The conducted studies have shown that the examined renewable energy sources differ in the degree of their impact on the values of voltage losses in the lines. The dynamics of the observed changes were illustrated mostly by the lag values (panel (c) in Fig. 7 and Fig. 8). In contrast to the PV generation, the wind turbine generation was in phase with the percentage voltage losses. Unlike for the wind turbine, for PV generation, there can be a larger discrepancy between the phase shift and the lag.

The black line in panel (a) in Fig. 7 and Fig. 8 illustrates the cone of influence. This line shows areas in the plot that may be affected by the edge effects. The presence of this phenomenon was made by stretching the wavelet function beyond the edges of the observed, finite-length time series.

Moreover, the final voltage loss waveform shapes (and consequently the wavelet coherence analysis plots) may also depend on the type of power lines in the distribution network. These lines can be either overhead or cables. Hence, the applicable type will influence the values of resistance and reactance, which are crucial in calculating voltage loss values.

The ease of preparing the examined time series is an advantage of applying the proposed approach. These time series may come from simulation software as well as from real-world systems. The proposed methodology can also be applied to a real system. Typical domains of usage may be, for example, smart grids or load flow studies (to augment the view of how renewable energy sources can affect electrical network parameters), and in forecasting electricity generation from RES and their future impact on the selected grid parameters. The modular design of the proposed model is another advantage. The presented methodology has strong potential for effective application in model validation of complicated real dynamic power systems that typically generate nonstationary time series data.

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6. Summary

Electric power systems and networks are becoming increasingly complex, resulting in the creation of time-based nonstationary signals, some of which are not yet fully understood [3, 58]. The features of these signals, such as trends or periodicities, may be the topic of interest for engineers and scientists. The dynamic development of renewable energy sources in the distribution grids requires a mature and long-term approach to their monitoring and analysis. For this type of complex system, there is a justified necessity to combine traditional modeling tools with modern signal-processing techniques.

The aim of this paper was to present a study of the impact of renewable energy sources' generation on voltage losses in the distribution grid lines using the wavelet coherence analysis. Compared to the solutions from the related work review, the introduced approach includes the use of the wavelet coherence for a more in-depth analysis of RES operation in the distribution grid. The final presentation of the wavelet coherence analysis using the main plot (panel (a) in Fig. 7 and Fig. 8) with an additional four graphs (panels (b), (c), (d) and (e) in Fig. 7 and Fig. 8) is a distinct advantage of this method and allows for easier visualization and interpretation of the obtained results.

Additionally, using the wavelet coherence, it can be clearly determined whether one signal "controls" the other. Furthermore, the use of voltage loss values instead of voltage drops allows for more accurate studies. In the future, the current model can be easily updated to include other data, especially with nonstationary data.

In recent years, the wavelet transform has proved to be a useful tool in many areas of electrical engineering (for example, [59–61]). The presented study extends and enriches the ongoing view of the impact of RES generation on the power grid. Hence, the wavelet transform studies can help emphasize further information that may be ignored or overlooked, particularly in fast-paced systems. The proposed method can be comfortably used by power system engineers in several ways. It can supplement the results of load flow calculations with added information on the voltage losses. It can also be used to support the available tools for forecasting voltage losses in the network, and it can be treated as a general tool for the more in-depth analysis of the RES influence on the grid. Possible paths for future research in this area may include the analysis of the coherence of other electrical parameters (for example, active and reactive power load) with renewable energy sources, the study of energy transmission losses, the study of power lines capacities matching the flow from RESs, or the study of the power quality in the distribution grid equipped with renewable energy sources.

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