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Changes in Farm Supply Voltage Caused by Switching Operations at a Wind Turbine

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Abstract: Renewable electricity sources are now widely used worldwide. Currently, the most common sources are those that use energy contained in biomass, water, sun, and wind. When connected to a medium-voltage grid, individual wind power plants must meet specific conditions to maintain electricity quality. This article presents field study results on the impact of switching operations (turning the power plant on and off) at a 2 MW Vestas V90 wind turbine on the voltage parameters at the connection point of a farm located 450 m from the source. The analysis showed that the wind turbine under study significantly affects customers' voltage near the source, causing it to increase by approximately 2.5%. Sudden cessation of generation during the afternoon peak causes a 3% voltage fluctuation, potentially affecting equipment sensitive to rapid voltage changes.

Keywords: wind power plant; voltage fluctuations; switching operations

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1. Introduction

Wind energy has been harnessed for centuries as a renewable but intermittent energy source. In addition, the forecasted depletion of fossil resources is forcing a search for alternatives, particularly with the prevailing trend in reducing the environmental impact of energy [1]. Wind turbines play a significant role in this respect. Wind turbines can be categorised into two main types, namely horizontal and vertical axis. Horizontal axis wind turbines offer a greater scope for optimising production by adjusting the blades' angle and shape to achieve greater efficiency [2]. There are two types of generators in wind power plants, asynchronous and synchronous, with power plants with asynchronous generators being used much more frequently in Poland [3,4]. There are two converters in these power plants, one on the rotor side to control the speed of the generator and the other on the grid side being mainly responsible for the output voltage parameters [5]. These devices are mainly responsible for the parameters describing the power quality generated in the power plant.

Wind power plants must maintain voltage levels within regulatory limits and ensure stable interaction with the power grid. Dynamic voltage changes at the point of connection to the distribution grid are one of the parameters describing the quality of electricity [6]. The operation of a wind power plant is associated with constant changes in the operating state, resulting from its design and the variability of wind strength and direction [7]. A noticeable effect of these changes at the point of source connection is the dynamic impact of wind turbines on the electricity grid. Ensuring the correctness of power supply to consumers located near the sources requires careful analysis of voltage quality and stability [8]. The stability of the grid voltage decreases as the number of power-unstable sources connected to it increases [9]. The diversity of wind turbine capacities and their distances from the nearest consumers makes it necessary to determine the response of the power system to the occurrence of a disturbance (the most significant change in power is characterised by the process of an emergency shutdown or start-up of a wind turbine in winds capable of reaching rated power) [10,11].

The generation of excess power in distributed power plants, relative to the demand of consumers in the immediate vicinity of the source, leads to an increase in network voltage [12]. The operation of consumers at increased voltage reduces the durability of the insulation materials and electronics used in them and, in extreme cases, can cause damage to them [13]. Voltage changes resulting from the operation of a power plant depend mainly on the stability of the grid and the power of the connected source [14]. A significant share of renewable energy sources in a given area can cause voltage instability, which can be manifested by exceeding the allowed grid voltage values, higher voltage dips, and voltage oscillations in the supply lines [15,16]. Voltage variations in the grid depend mainly on the power generated and the impedance of the system (length and cross-section of the cables and resistance of the connections) [17]. The smallest voltage changes occur near the transformer station and increase with the length of the supply line [18]. In the case of small wind turbines connected to a low-voltage power grid, their effect on voltage distortion is negligible [19,20]. The occurrence of increased voltage distortion coefficient values in power grids is mainly due to the presence of non-linear loads in the power system [21,22].

Wind power plant research is widely reported in the scientific literature. The research topics can be divided into three main groups, namely production forecasting [1,23], power generation optimisation [24–26] (including costs), and the impact of power plants on the environment [27,28]. Energy from renewable energy sources is perceived and treated as emission-free. Thus, it is not burdened with increasing allowance costs related to carbon dioxide emissions. The field research carried out by the authors was intended to supplement the knowledge of the impact of wind power plants on the supply voltage of consumers near the source. This paper addresses the issue of the impact of switching operations at the Vestas V90 power plant with a capacity of 2 MW on the parameters describing the voltage occurring at the point of connection of a rural farm located at a distance of approximately 450 m from the source.

2. Materials and Methods

Researchers conducted the study at a farm's power supply point that specialises in dairy cows. The farm is located near a wind turbine; the distance between these facilities, measured by the length of the medium-voltage power line, was 450 m. Both facilities were connected via transformer stations to the 15 kV network. The farm was approximately 9.5 km from the main regional power supply point, with a 70 mm^2 aluminium–steel core power line supplying both facilities. The short-circuit power at the connection point of the wind power plant was 49 MVA, while the reactance-to-resistance ratio at this point of the system was 1.11. The wind power plant operates at a rated power factor of cos = 1. The study consisted of recording selected voltage parameters occurring at the farm connection point, during the start-up of the wind farm (with winds allowing the rated power to be reached) and during the emergency shutdown of the power plant (from a power close to the maximum achievable power). These operating states significantly impact voltage values at the connection point.

Measurements were conducted in April, when low-voltage line loads were highest due to farm animals residing in barns. The sites surveyed were located in an area where snowy winters are most common during the winter months (December to March), which can cause ice on the wings as well as ice on the overhead line wires (which can cause emergency disconnections of the power station from the electricity grid). Measurements were carried out during two times of the day, once during the hours around noon, when the load is relatively low, and during the evening hours, when the load is highest (mainly due to the milking of dairy cows taking place at this time).

A portable MAVOWATT 240 power quality analyser from GOSSEN METRAWATT (Nuremberg, Germany), with a calibration certificate issued by the Drantez Laboratory, was used to record changes in farm voltage values resulting from switching activities at the wind farm. This analyser is designed to measure and record the performance of a three-phase power network in accordance with the highest global standards, such as IEC 61000-4-30 [29] Class A (all measured quantities), IEC 61000-4-7 [30] (harmonics), IEEE 1159 [31], IEEE 519 [32], and IEEE 1453 [33]. The device allows measurements in installations in the CAT III and CAT IV categories. Voltage was measured with an accuracy of ±0.1% of nominal voltage.

The technical data of the wind turbine, whose effect on the farm's supply voltage was studied, are shown in Table 1.

Table 1. Parameters of the wind turbine.

Parameter	Value
Type of power plant	VESTAS V90–2.0 MW
Blade diameter	90 m
Number of turbine blades	3
Swept surface	6362 m^2
Speed range	9–14.9 rpm
Turbine power adjustment	Pitch control
Tower height	105 m
Tower construction type	steel tube
Generator type	synchronous
Rated active power of the generator	2000 kW
Rated voltage of the generator	690 V
Rated frequency of the generator	50 Hz
Starting wind speed (switch on)	3.5 m/s
Rated wind speed (rated power)	13 m/s
Maximum wind speed (standstill)	25 m/s

In order to determine the influence of switching operations on the parameters describing the quality of the power supply voltage to the farm under study, the measured values were compared with the requirements of the relevant standards. The requirements for wind turbines temporarily connected to the medium-voltage grid according to EN 50160 [34] are shown in Table 2.

Table 2. Requirements for grid-connected wind turbines [34].

Parameter	Requirements
Frequency deviation	The frequency variation should not exceed +/−1% of the rated frequency.
Voltage deviation	The voltage at the facility connection point should be within +/−10% of the rated voltage.
Voltage fluctuations	The wind turbine should not cause sudden changes and voltage spikes exceeding 3% of the rated voltage.
Voltage distortion	The total voltage distortion coefficient THDu value should be less than 3% for wind power plants connected to a grid with a rated voltage higher than 1 kV and not higher than 30 kV.

The rated voltage at the power point of the farm under study is 230 V (phase voltage) and 400 V (phase-to-phase voltage). The occurrence of voltage values above 253 V (440 V) or below 207 V (360 V) in the system should be considered non-compliant values, as shown in Table 2.

The supply voltage frequency is the number of repetitions in the time waveform of the fundamental component of the supply voltage measured over a specified time interval. The frequency deviation is described as the difference between a given value and the rated value of the frequency exhibited during regular operation of the power system over at least a few seconds.

$$\Delta f_{\%} = \frac{f_i - f_N}{f_N} \cdot 100\% \quad (1)$$

where $\Delta f_{\%}$—percentage frequency deviation; f_i—actual (measured) frequency value; and f_N—rated network frequency.

A change in the value of the supply voltage is defined as an increase or decrease in the value of the voltage. There are two types of change in voltage value, slow changes called voltage deviation and fast changes called voltage fluctuations. A voltage deviation is defined as the difference between the actual and rated voltage values of the network occurring over a long time interval (of the order of seconds).

$$\Delta U_{\%} = \frac{U_i - U_N}{U_N} \cdot 100\% \quad (2)$$

where $\Delta U_{\%}$—percentage voltage deviation; U_i—actual (measured) voltage value; and U_N—rated mains voltage.

Voltage fluctuations are defined as the difference between the actual and rated voltage values of the network occurring in two consecutive units of time (on the order of milliseconds).

$$d = \frac{U(t_1) - U(t_2)}{U_N} \cdot 100\% \quad (3)$$

where d—percentage voltage fluctuation; $U(t_1)$—actual (measured) rms voltage value at time t_1; $U(t_2)$—actual (measured) voltage value at time t_2; and U_N—rated network voltage.

The effect of a change in the power generated at a power station on the voltage level at the power station connection point can be described by the following relation [35]:

$$\Delta U = \frac{1,1 \cdot \Delta P \cdot U_N \cdot |1 - \mathrm{tg}\varphi_k \cdot \mathrm{tg}\varphi_E|}{S_k \cdot \sqrt{1 + (\mathrm{tg}\varphi_k)^2}} \quad (4)$$

where ΔU—voltage change caused by the power variation in the source; S_k—short-circuit power at the source connection point; ΔP—change in power generated by the source; U_N—nominal network voltage; $tg\varphi_E$—nominal power factor of the source; and $tg\varphi_k$—tangent of the short-circuit impedance angle at the source connection point, calculated as the ratio of the resistance (R_k) and reactance (X_k) of the power network.

$$\mathrm{tg}\varphi_k = \frac{X_k}{R_k} \quad (5)$$

Using the data characterising the analysed power system (provided at the beginning of this section) and relation (4), it is possible to determine the theoretical voltage change caused by the power variation generated by the wind power plant (in the case of an emergency shutdown, this would mean a change from the nominal power (2 MW) to 0). In the analysed case, the emergency shutdown of the plant resulted in a voltage change of 3.01%. It is not possible to theoretically determine the voltage change occurring during the startup process of the plant, as this would first require an experimental determination of the power increase gradient during this process.

The indicator most commonly used in practice to describe voltage distortion is the total harmonic distortion factor (THD), which defines the percentage ratio of the rms value of the higher harmonics to the rms value of the fundamental harmonic.

$$THD_U = \frac{\sqrt{\sum_{h=2}^{\infty} U_h^2}}{U_1} \cdot 100\% \quad (6)$$

where U_h—rms value of the voltage of the h-th harmonic; U_1—rms value of the voltage of the first harmonic; and h—harmonic order.

The impedance of the power system defined for individual harmonics can be determined from the following relation:

$$\underline{Z_h} = \sqrt{h} \cdot R_k + jX_k \tag{7}$$

Considering the values provided in Table 3 and relations (6) and (7), the total harmonic distortion coefficient (THD_U) for the analysed VESTAS V90 2.0 MW wind power plant can be determined. This value, at the connection point of the plant, according to data provided by the manufacturer and the characteristics of the power network, is THD_U = 2.11%. It should be emphasised that the calculation does not take into account the increase in short-circuit power resulting from the plant's connection to the power system.

Table 3. The harmonic content in the current for the analysed VESTAS V90 2.0 MW wind turbine (Aarhus, Denmark), as provided by the manufacturer in the "Windtest" document.

Order	Output Power [W]	Harmonic Current [% of I_N]	Order	Output Power [W]	Harmonic Current [% of I_N]
2	2000.9	0.2	3	1030.9	0.1
4	1214.6	0.2	5	605.7	0.8
6	259.1	0.2	7	805.7	0.2
10	1877.6	0.1	11	1735.4	0.5
32	48.5	0.1	13	1366.8	0.2
46	1646.1	0.1	29	480.6	0.1
48	1999.6	0.2	31	38.4	0.2
50	45.9	0.1	33	280.5	0.1
			35	852.9	0.1

To determine the impact of the wind power plant on the power network at its connection point, a weekly test was conducted to assess the quality parameters of the energy generated at the source. Measurements were carried out in accordance with [34] over one week. Analysis of the data obtained during measurements shows that the wind power plant meets the [34] requirements for the quality of electricity it generates. The 95th percentile (defined as the highest value obtained in 95% of the registration time over the week) of voltage frequency variation during the registration period was 0.06%. The largest recorded voltage deviation was in phase L3 and amounted to 7.12%—Table 4.

Table 4. Results of the weekly study of percentage voltage deviation at the connection point of the power plant during its operation.

Phase	L1	L2	L3
Average value	5.041	4.950	5.508
Minimum value	2.866	2.866	3.400
Maximum value	7.924	8.013	8.417
95th percentile	6.615	6.592	7.119

The results of the total harmonic distortion coefficient (THD_U) values recorded at the connection point of the power plant (on the medium-voltage busbars) are presented in Table 5.

Table 5. Results of the weekly study of the voltage distortion coefficient at the connection point of the power plant during its operation.

	THD_{UL1} [%]	THD_{UL2} [%]	THD_{UL3} [%]
Average value	1.142	1.117	1.091
Minimum value	0.480	0.410	0.400
Maximum value	1.860	1.860	1.800
95th percentile	1.690	1.660	1.590

3. Results

In order to determine the impact of the wind power plant on the voltage parameters of the grid supplying the farm located near the power plant, a study of the dynamic impact of the source was carried out. To this end, changes in voltage parameters during the start-up and emergency shutdown of the power plant were recorded. In order to take into account the diurnal variability of the load and thus the voltage values at the point supplying the farm, the tests were carried out twice—during the midday valley and the evening peak. Figures 1 and 2 show the recorded changes in phase and phase-to-phase voltage values during the commissioning process of the wind turbine in the South Valley.

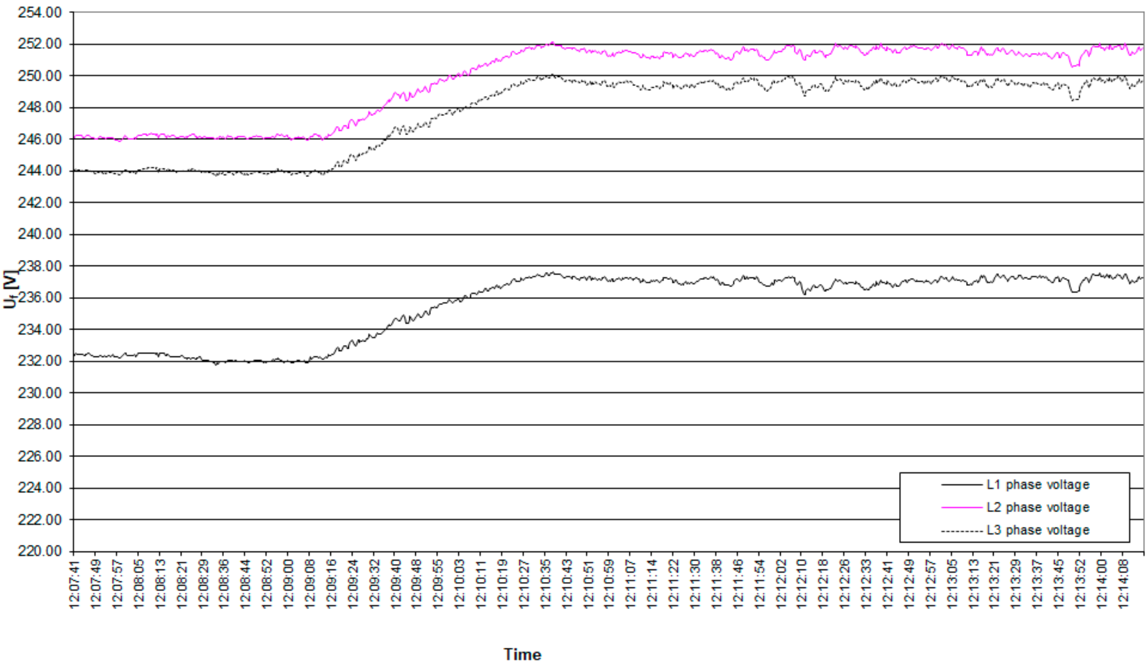

Figure 1. The profile of phase voltage values at the farm recorded during wind turbine commissioning—peri-monsoon hours.

From the analysis of the waveforms shown in Figure 1, it can be seen that the voltage in phase L1 differs significantly from the voltages present in the other phases. This asymmetry can cause the malfunction of three-phase equipment installed on the farm, especially equipment with electric motors. However, it is not a result of the power plant. As expected, the voltage at the farm supply point increases during the power plant's start-up, taking on values close to the maximum permissible values. Nevertheless, they are within the limits described in Table 2.

In the case of phase-to-phase voltages, the asymmetry of values is no longer as noticeable—the recorded voltage values differ by no more than 4 V—see Figure 2. Here too, an apparent increase in voltage is visible during the start-up of the power plant. These are also values that are within the limits described in Table 2. Figure 3 shows a linear relationship between the voltage at the farm's connection point and the power generated by the wind turbine.

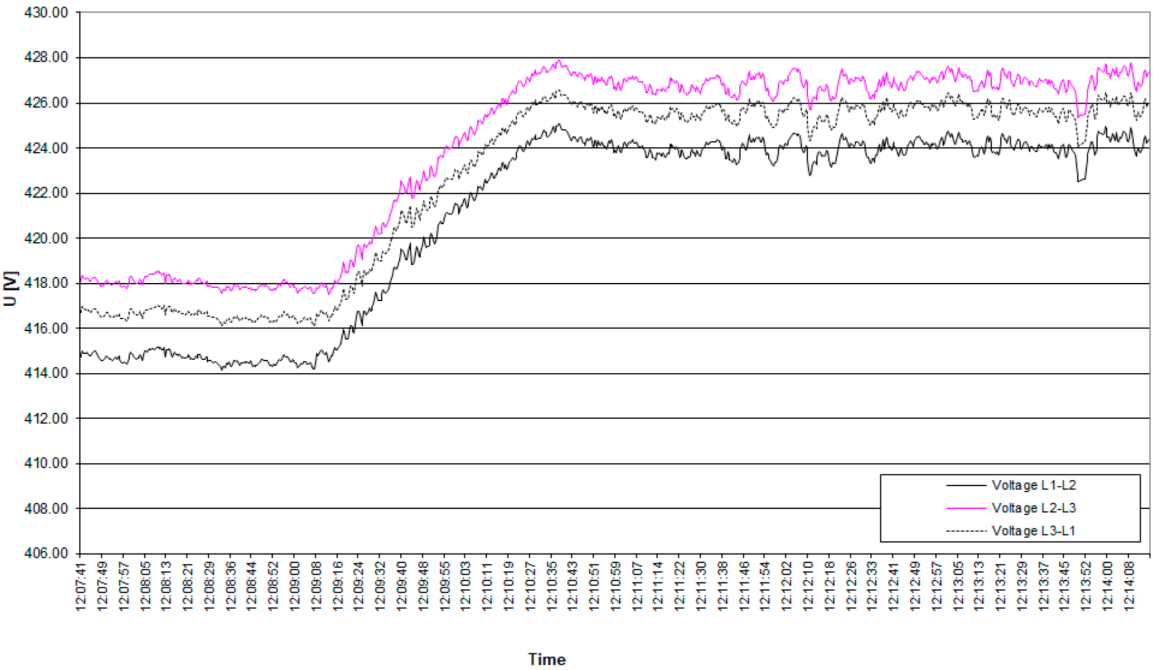

Figure 2. The profile of phase-to-phase voltage values at the farm recorded during the wind turbine start-up—peri-monsoon hours.

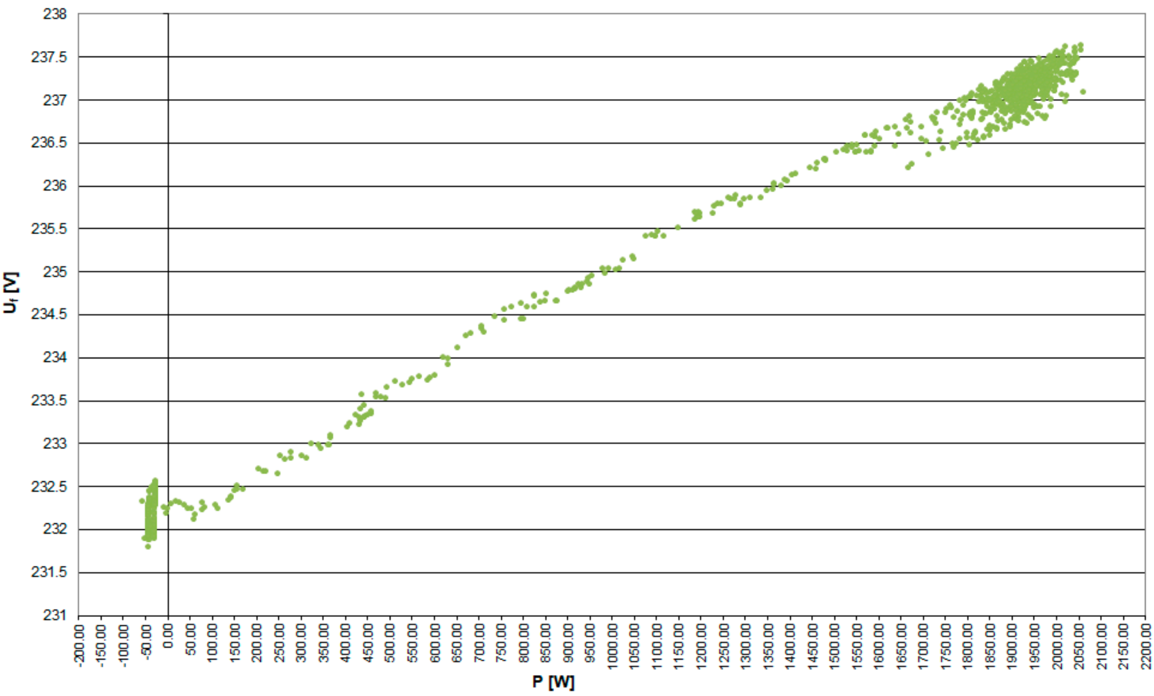

Figure 3. The voltage dependence of the wind turbine generated power—peri-monsoon hours.

Figure 4 shows the recorded change in the total voltage distortion coefficient THD_U over the same time period. In this case, the asymmetry of the recorded values in the different phases is also apparent. In each phase, a straightforward (approximately 20%) decrease in the recorded THD_U coefficient is visible as the power generated in the power plant increases. The THD_U value is within acceptable standards at each recorded point in time.

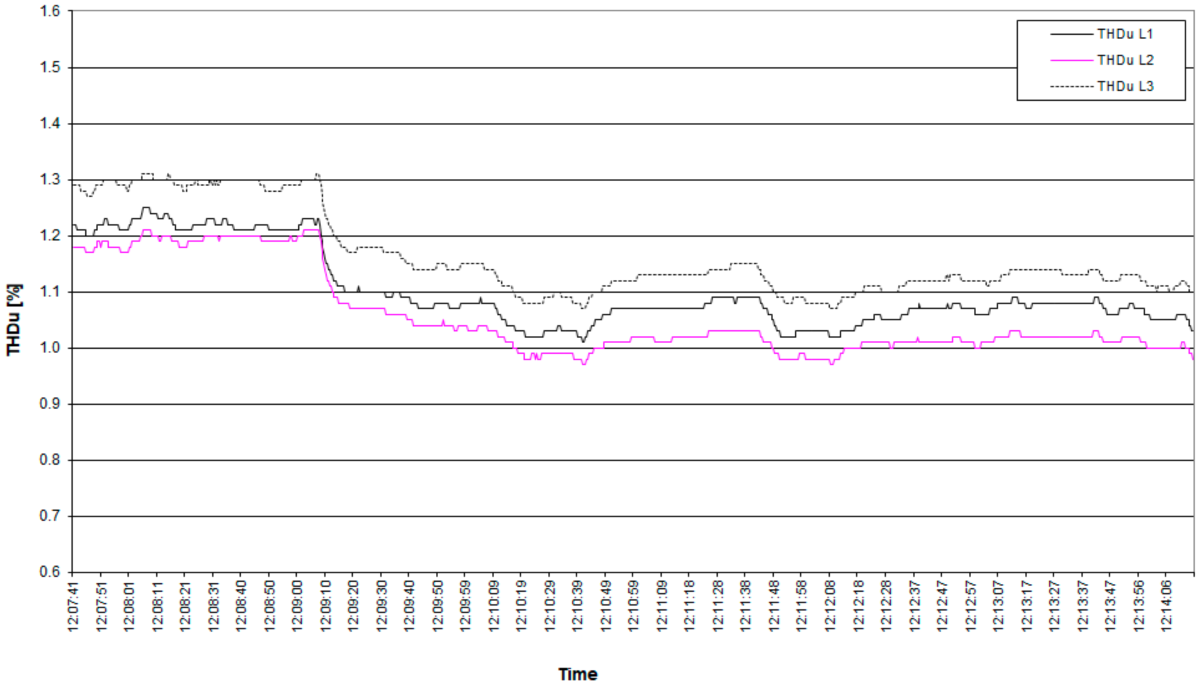

Figure 4. The profile of the THD_U voltage distortion coefficient at the farm recorded during wind turbine commissioning around noon.

Figure 5 shows the variation in voltage frequency values recorded during wind turbine commissioning. In this case, however, any change in value due to a change in the power generated by a nearby source is not noticeable, and the recorded deviations are within the regulatory limits.

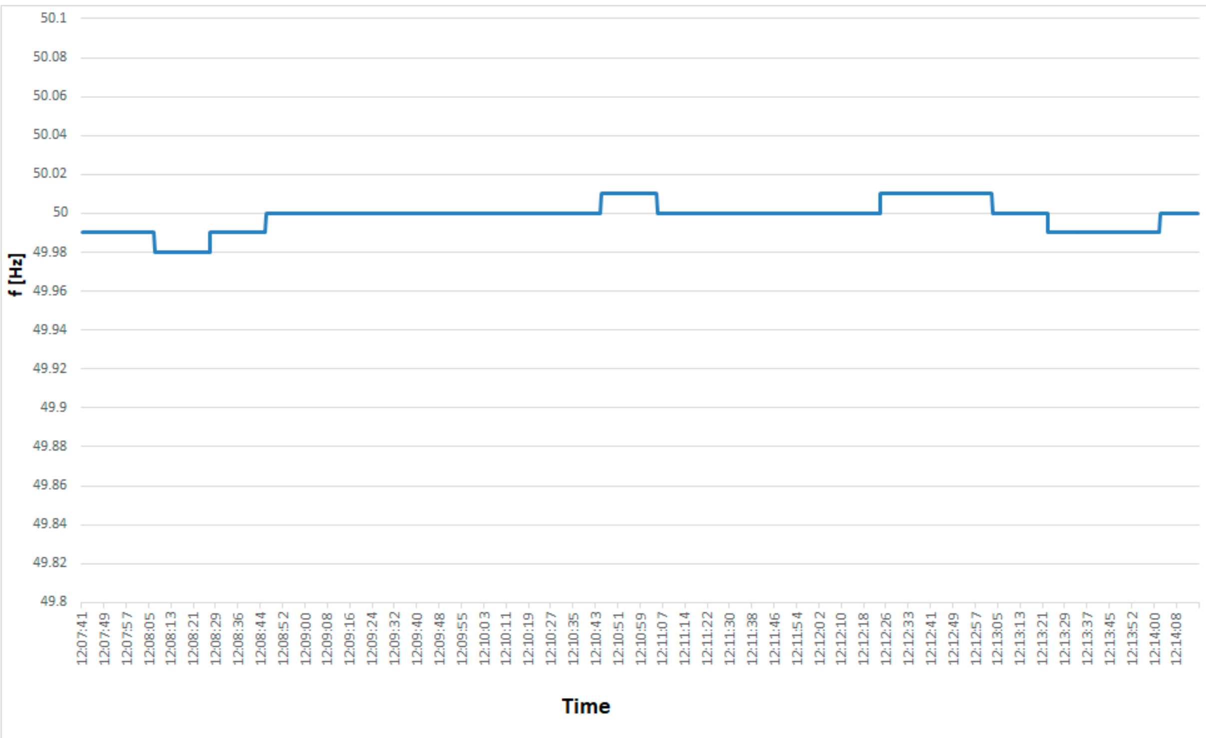

Figure 5. The profile of the frequency value of the voltage at the farm recorded during the wind turbine start-up around noon.

Another activity whose effect on the grid voltage was recorded was the emergency shutdown of the wind turbine. In this case, the power generated by the source dropped from about 2 MW to 0 in <1 s. The recorded changes in the analysed voltage parameters at the farm connection point are shown in Figures 6–9.

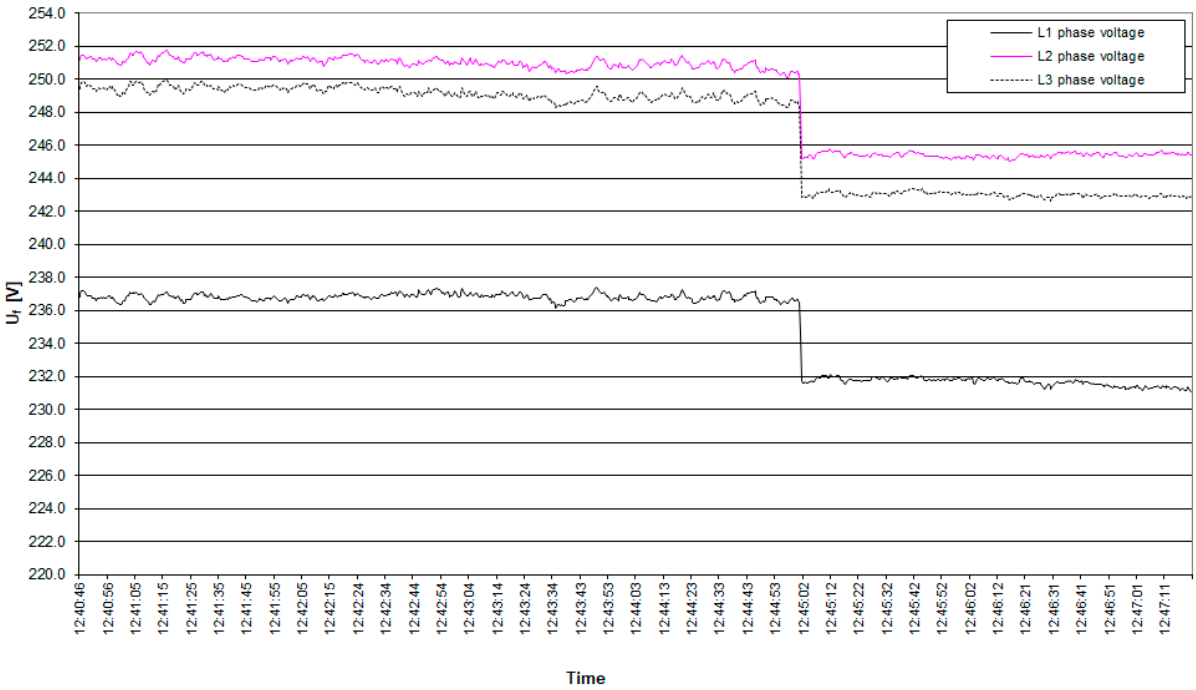

Figure 6. The profile of phase voltage values at the farm recorded during the wind turbine start-up around noon.

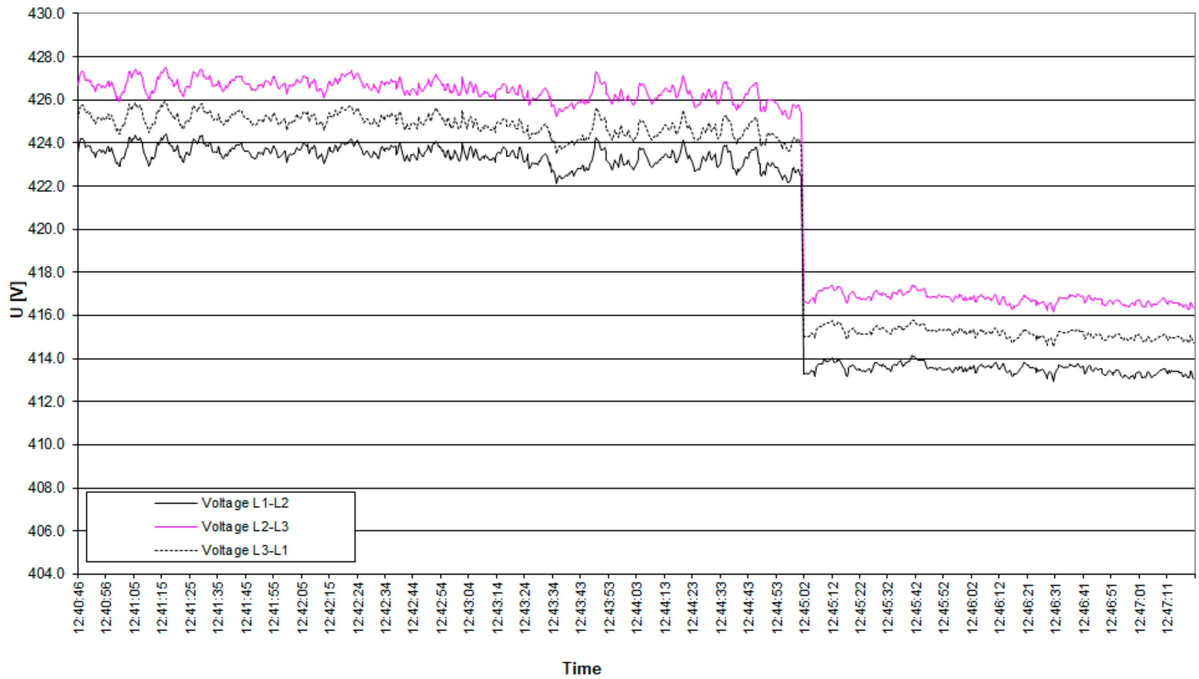

Figure 7. The profile of phase-to-phase voltage values at the farm recorded during a wind turbine shutdown during peri-monsoon hours.

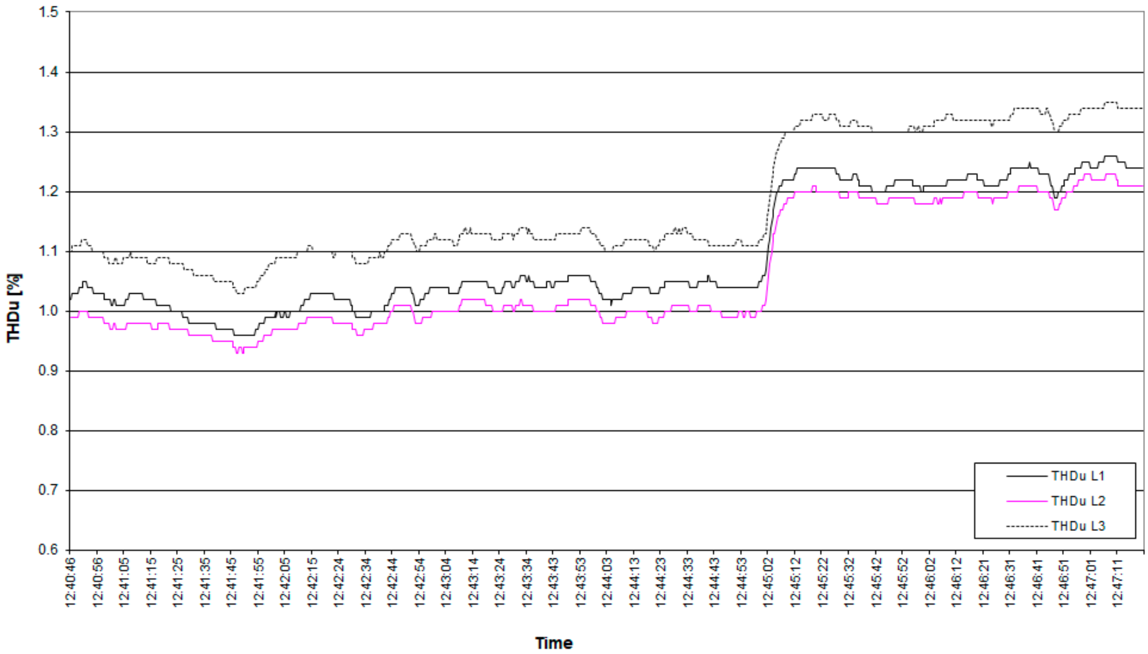

Figure 8. The profile of the THD_U voltage distortion coefficient at the farm recorded when the wind turbine stopped around noon.

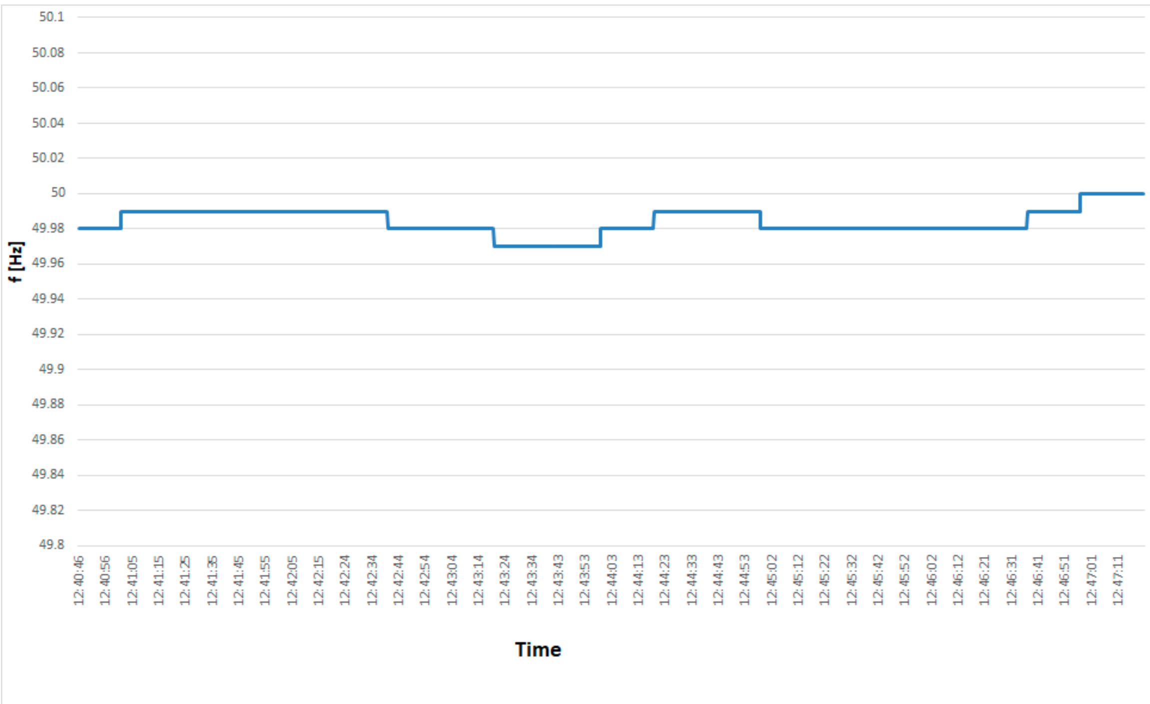

Figure 9. The profile of the frequency value of the voltage at the farm recorded during the wind turbine shutdown around noon.

In the case of phase voltages (Figure 6) and phase-to-phase voltages (Figure 7), it is apparent that the recorded values decrease when the power station is stopped. Despite these changes, the voltage values are always more significant than the rated value.

In the case of the voltage distortion coefficient THD_U (Figure 8), there is a noticeable increase (around 20%) in its value after the wind turbine is switched off. Switching off the source did not cause any noticeable change in the frequency values (Figure 9).

To finalise the analysis, studies were conducted on the effects of switching operations at the wind turbine on the voltage parameters within the farm's power supply system during the evening peak, when the main voltage tends to be lower. During the afternoon, farmers often report problems with the operation of electronic equipment (including milking robots) due to the voltage levels in the grid being too low. Figures 10 and 11 show the changes in voltage values resulting from the commissioning of the wind turbine.

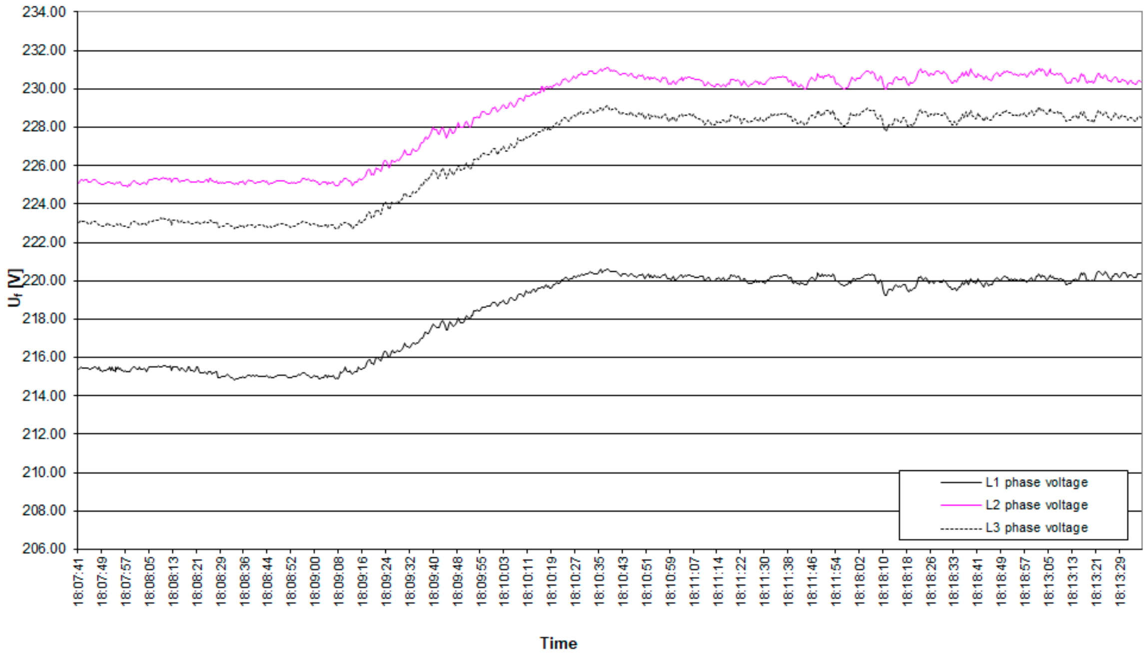

Figure 10. The profile of phase voltage values at the farm recorded during wind turbine commissioning—evening hours.

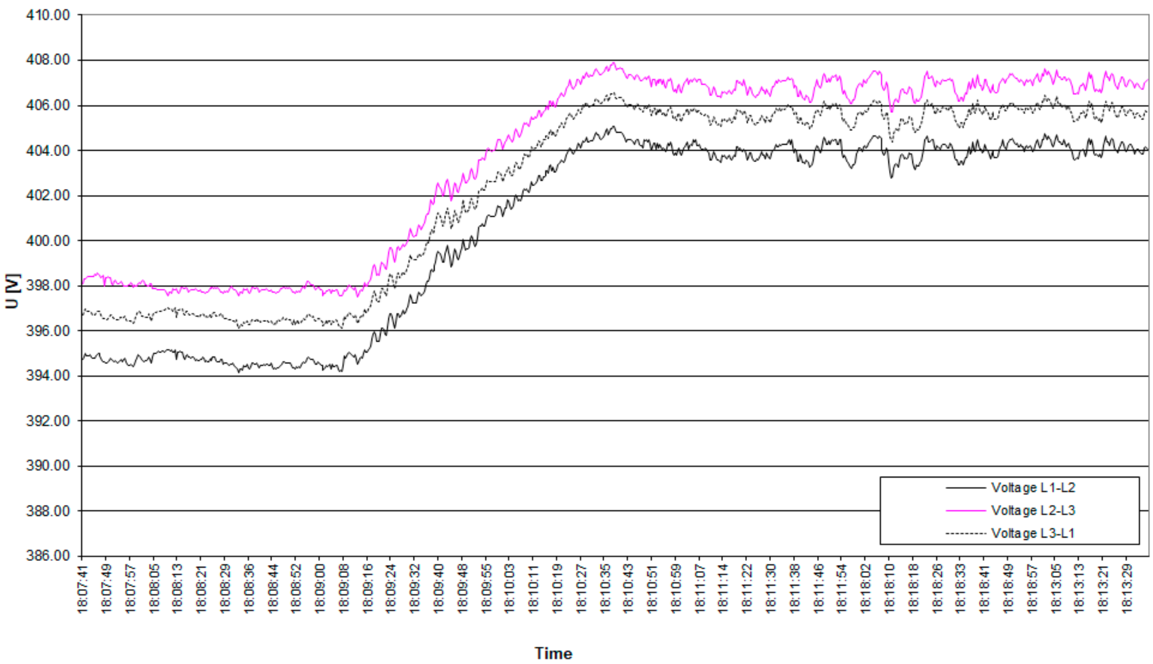

Figure 11. The profile of phase-to-phase voltage values at the farm recorded during wind turbine commissioning—evening hours.

During the evening hours, phase voltage asymmetry is also evident. However, prior to the start-up of the power plant, the voltage was significantly lower than the rated voltage. Also, during the evening hours, the relationship between the voltage at the farm connection point and the power generated at the wind turbine is rectilinear, see Figure 12.

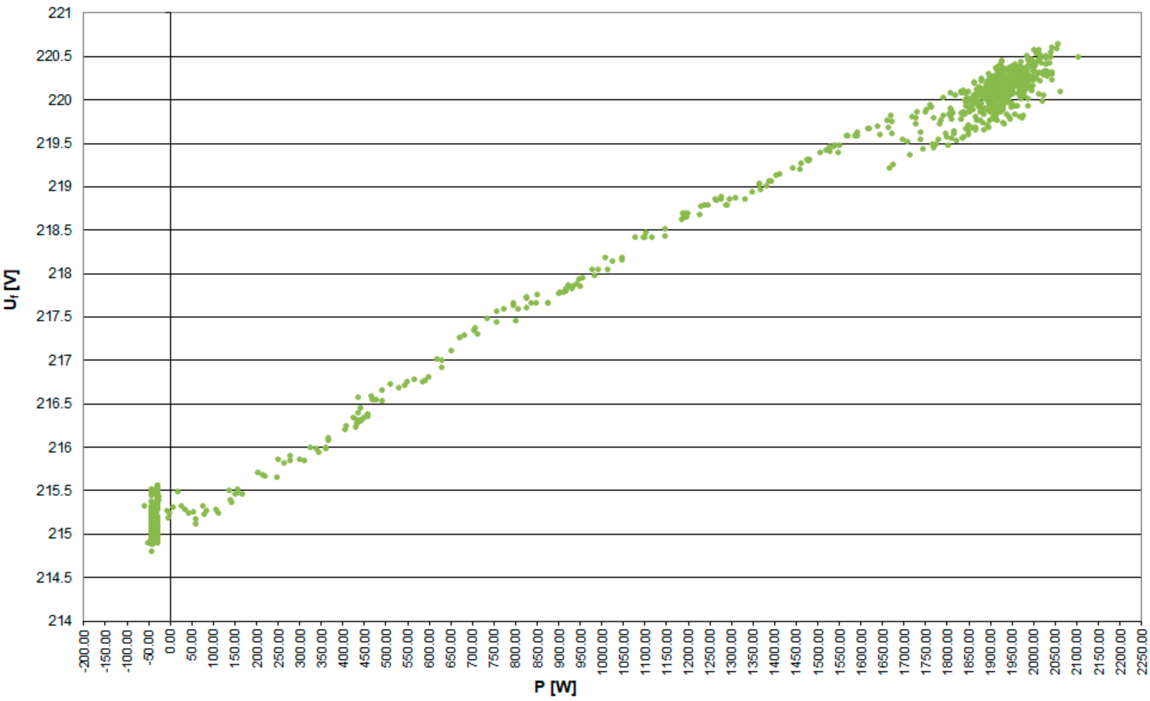

Figure 12. Voltage dependence (U_f) of wind power generation (P)—evening hours.

Analogously, as in the peri-monsoon hours, increased power generated at the source decreased the voltage distortion coefficient THD_U (Figure 13). As in the previous case, the power plant start-up's effect on the supply voltage's frequency level was not registered, see Figure 14.

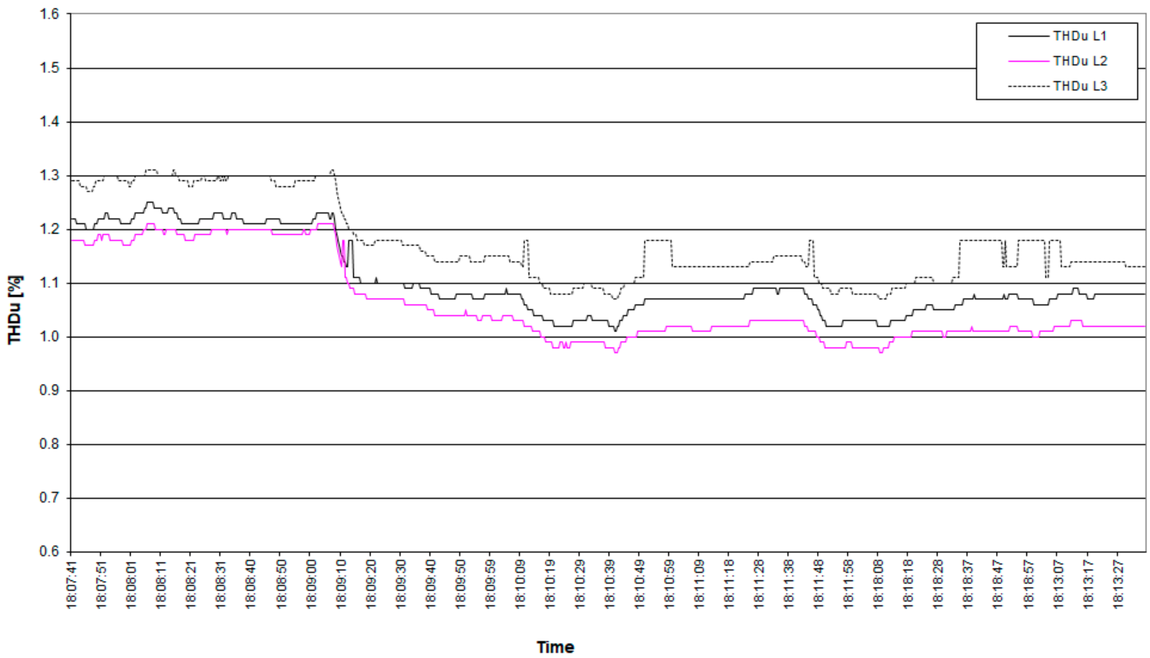

Figure 13. The profile of the *THDu* voltage distortion coefficient at the farm recorded during wind turbine commissioning—evening hours.

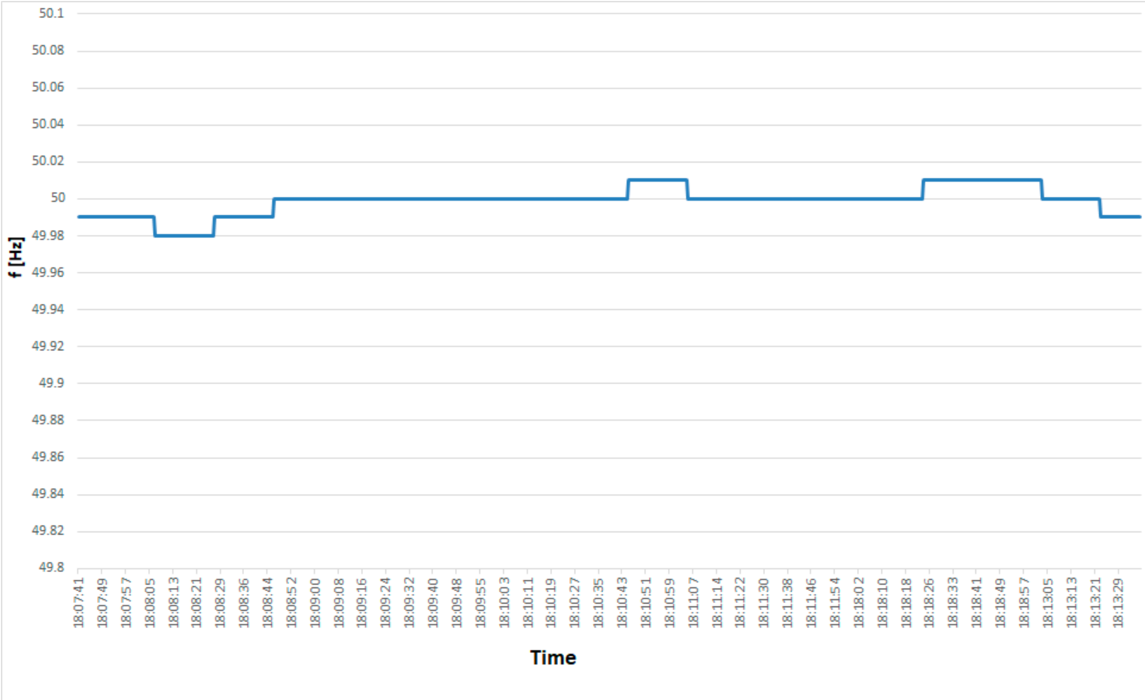

Figure 14. The profile of voltage frequency values at the farm recorded during a wind turbine commissioning—evening hours.

The next step, analogous to the studies carried out around noon, was an emergency shutdown of the wind turbine in the evening. As seen from the waveforms shown in Figures 15 and 16, the generation shutdown caused a significant drop in voltage values at the connection point of the farm under study. It should be noted that after the power plant shutdown, the voltage at phase L1 dropped to 214 V, which can cause the malfunction or stoppage of equipment installed on the farm and sensitive-to-low levels of and rapid changes in the supply voltage.

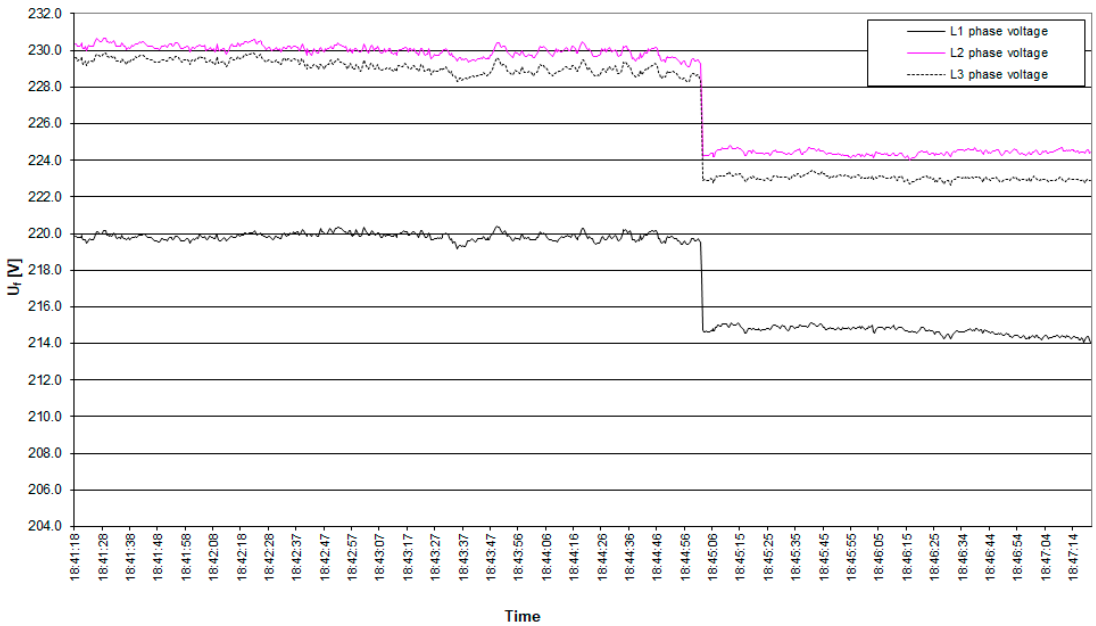

Figure 15. The profile of phase voltage values at the farm recorded during a wind turbine shutdown—evening hours.

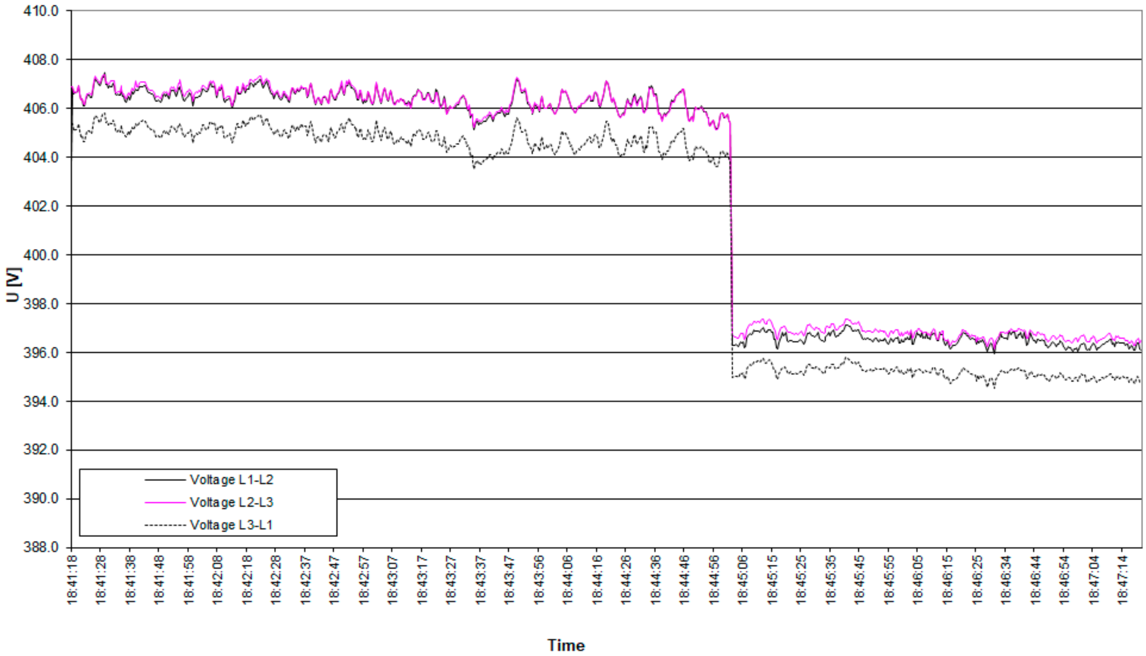

Figure 16. The profile of phase-to-phase voltage values at the farm recorded during a wind turbine shutdown—evening hours.

As with the previous measurements, the recording of the power station shutdown in the evening showed a positive effect of the power station operation on the voltage distortion factor (an approximately 20% increase in THD_U was observed during the power station shutdown), see Figure 17. There was also no correlation between the power generated and the voltage frequency value, as shown in Figure 18.

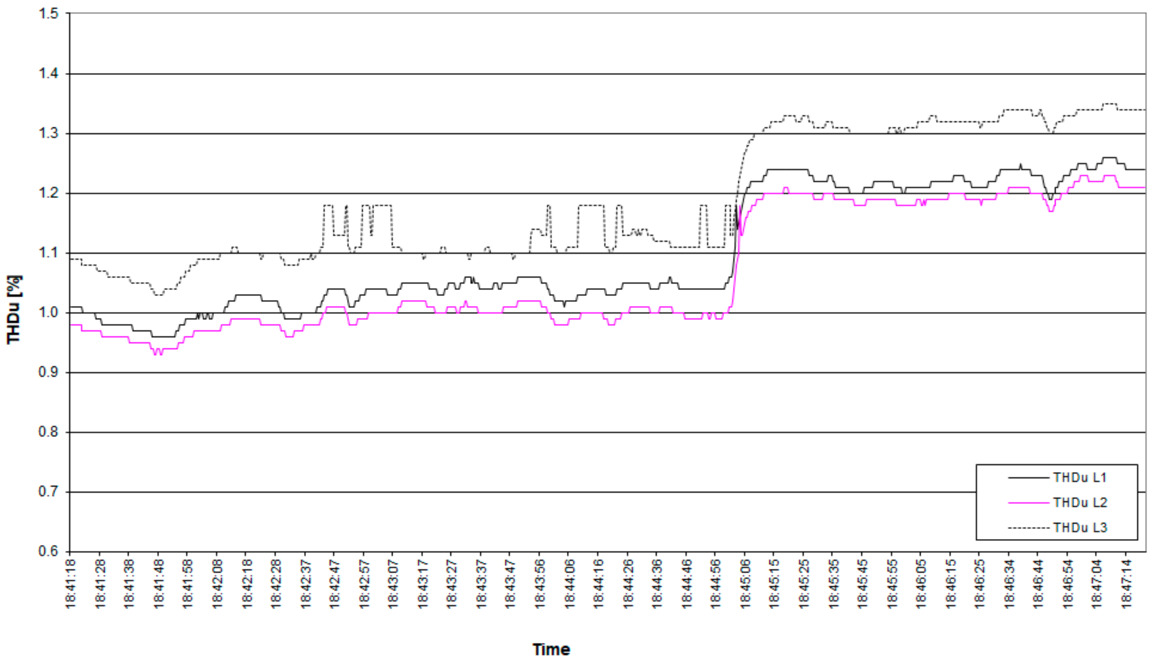

Figure 17. The profile of the voltage distortion coefficient THD_U at the farm recorded during a wind turbine shutdown—evening hours.

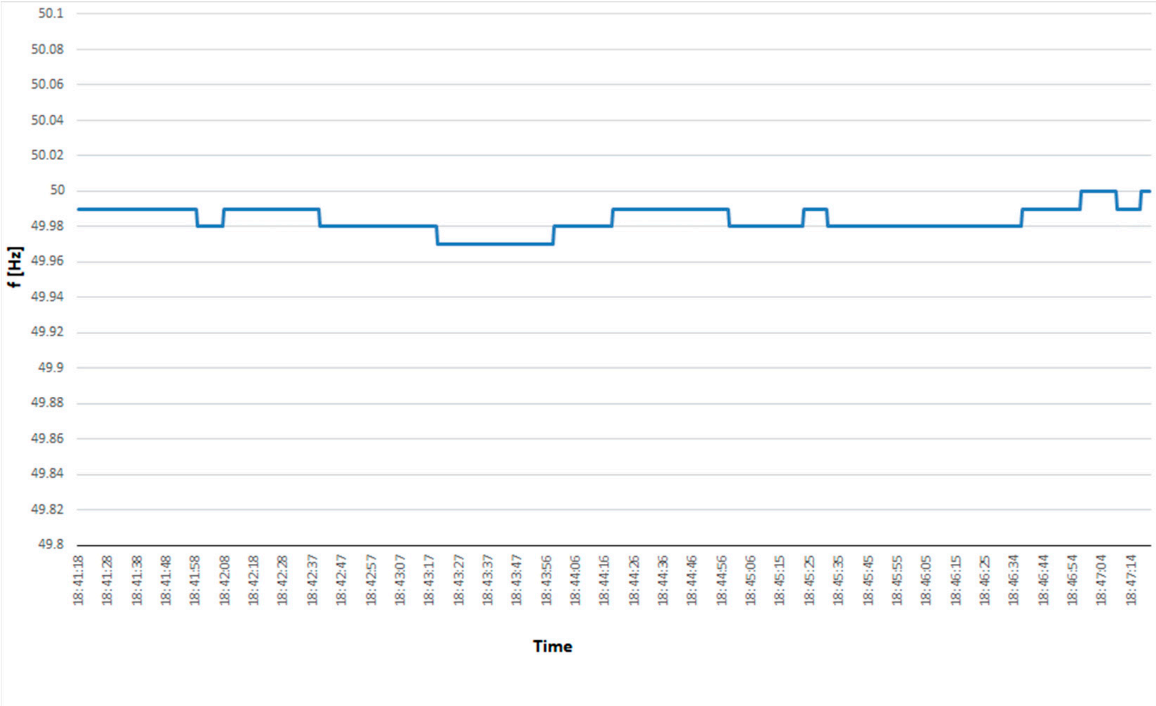

Figure 18. The profile of voltage frequency values at the farm recorded during a wind turbine shutdown—evening hours.

4. Discussion

In order to check whether the switching activities in a wind turbine violate the technical and regulatory requirements described in Table 2 with regard to the change in the voltage supply to a farm located in the immediate vicinity of the power plant, it is necessary to take a closer look at the recorded voltage values. The voltage values recorded during the commissioning of the wind turbine in the afternoon hours are shown in Table 6, and Table 7 contains the corresponding values recorded in the evening hours.

Table 6. Results of the analysis of voltage levels at the farm during the commissioning of the wind power plant—midday hours.

	U L1–L2	**U L2–L3**	**U L3–L1**
Voltage values with the wind farm disconnected			
	[V]	[V]	[V]
Average value	415.302	418.486	417.170
Minimum value	414.146	417.515	416.118
Maximum value	419.068	422.043	420.742
Voltage values after commissioning of the wind farm			
	[V]	[V]	[V]
Average value	424.032	426.900	425.648
Minimum value	422.795	425.732	424.328
Maximum value	424.819	427.664	426.444
Voltage fluctuations resulting from the switching on of the wind farm			
	[%]	[%]	[%]
Average value	2.059	1.971	1.992
Minimum value	0.882	0.866	0.845
Maximum value	2.512	2.373	2.422

Table 7. Results of the analysis of voltage levels at the farm during commissioning wind turbine—evening hours.

	U L1–L2	**U L2–L3**	**U L3–L1**
Voltage values with the wind farm disconnected			
	[V]	[V]	[V]
Average value	395.301	398.481	397.179
Minimum value	394.146	397.515	396.118
Maximum value	399.068	402.043	400.742
Voltage values after commissioning of the wind farm			
	[V]	[V]	[V]
Average value	404.046	406.917	405.660
Minimum value	402.795	405.732	404.381
Maximum value	404.819	407.664	406.444
Voltage fluctuations resulting from the switching on of the wind farm			
	[%]	[%]	[%]
Average value	2.164	2.073	2.091
Minimum value	0.925	0.909	0.900
Maximum value	2.636	2.490	2.541

Based on the values in Table 5, it can be concluded that the voltage at the farm connection point during wind turbine operation exceeds the rated value by approximately 6.7% and that the start-up process increases the voltage by approximately 2.5%. These are significant values but within the limits of the currently applicable regulations [34]. In the absence of generation, there is an overshoot of the voltage rating during midday hours, but it does not exceed 5.5%.

During the evening hours, when the wind turbine is switched off, the voltage on the grid supplying the farm is lower than the rated voltage by about 2.5%, as shown in Table 7. It should, therefore, not affect the operation of the equipment installed on the farm. The power plant start-up causes the voltage to increase above the rated voltage (by about 1.7%). The recorded voltage change is a maximum of 2.636% and is less than the 3% required by the regulations.

The results of the analysis of the changes in voltage values resulting from the emergency shutdown of the wind turbine are shown in Table 8 (for the circadian hours) and Table 6 (for the evening hours). In the peri-morning hours, with the voltage approximately 6.7% above the rated value, the generation outage resulted in a maximum voltage drop of 2.77% (Table 7). In this case too, both the level and the voltage fluctuation caused by the generation stoppage at the power station are within the limits allowed by current regulations [34].

Table 8. Results of the analysis of voltage levels at the farm during the emergency shutdown of the wind farm—peri-monsoon hours.

	U L1		**U L2**		**U L3**	
	[V]		**[V]**		**[V]**	
Voltage values before the wind farm shutdown	424.249		427.300		425.618	
Minimum voltage values after emergency shutdown of the wind farm	413.170		416.561		414.912	
Maximum voltage variation due to emergency shutdown of the wind farm	[V]	[%]	[V]	[%]	[V]	[%]
	11.08	2.770	10.74	2.685	10.71	2.676

Switching off the power plant in the evening causes a much higher voltage variation at the farm connection point, see Table 9. Noticeably, the permissible value of voltage fluctuation in phase L1, caused by switching off the wind power plant, is exceeded; the recorded variation is 3.017%. It is a value very close to the one calculated by the authors based on Equation (4). The registered voltage fluctuations are minor but close to the permissible value in the other phases. Such large short-term voltage fluctuations can cause malfunctions in voltage-sensitive equipment. Therefore, when such irregularities are noticed, a voltage stabiliser should be installed in the power supply system of the machines concerned.

Table 9. Results of the analysis of voltage levels at the farm during the emergency shutdown of the wind farm—evening hours.

	U L1		**U L2**		**U L3**	
	[V]		**[V]**		**[V]**	
Voltage values before the wind farm shutdown	407.249		407.300		405.618	
Minimum voltage values after emergency shutdown of the wind farm	395.180		396.021		394.221	
Maximum voltage variation due to emergency shutdown of the wind farm	[V]	[%]	[V]	[%]	[V]	[%]
	12.07	3.017	11.28	2.820	11.40	2.849

These results show that analysing transients in electricity networks is both scientifically and practically significant. Therefore, continuous transient monitoring becomes crucial, particularly in large rural power grids [36]. In analysing the impact of wind power plants on power grid parameters, it is important to confirm that field studies support the presented conclusions. Basing observations only on the results of calculations or laboratory tests may lead to incorrect conclusions. Such a situation occurred in a publication by Shalukho [37], who, based on tests carried out on a laboratory model of a wind power plant, showed that the modelled power plant increases the voltage distortion in the grid. The authors came to similar conclusions when the value of the voltage strain coefficient led by an operating wind turbine was determined from relationship (6) (using the grid parameters and data provided by the wind turbine manufacturer). These calculations do not take into account the increase in the value of the short-circuit power resulting from the connection of the power plant to the power system and the correlation of individual harmonics generated by the power plant and occurring in the power grid. As shown in this article (Figures 4, 7, 13 and 17), an increase in power generated from the power plant reduces the voltage distortion coefficient THD_U by approximately 20%. The positive effect of the wind power plant on the medium-voltage grid has also been presented in other publications [38–40]. The analyses carried out by the authors show that a change in the value of the voltage strain coefficient value may have several causes. Due to the fact that the power plant is connected to the grid through an internal power electronic system, it should introduce additional disturbances into the grid [38]. However, the latest wind power plants, according to the data provided by their manufacturers in data sheets, introduce negligible current and voltage distortions into the grid [39]. It should be remembered that the voltage and current generated in the power plant may be partly in antiphase to the disturbances occurring in the network, causing their amplitude to decrease. The second, according to the authors, more important argument confirming the positive impact of renewable energy sources on voltage distortion is a significant increase (the greater the power of the power plant) in the value of the short-circuit power at the source connection point. Increasing the short-circuit power translates into an increase in the stability of the grid at a given point of the power system, which makes it less sensitive to disturbances generated by the connected devices [40].

The conclusion of this research is limited to the following aspects to be addressed by future studies:

(1) The seasonal variability of the power profile variability in the voltage profile and quality delivered to consumers was not analysed. Unexpected violations in the voltage profile and quality may be observed in different months and seasons.
(2) The impact of extreme weather events on the wind power profile and voltage, for example, icy conditions, was not analysed.
(3) The type of voltage stabiliser technology, for example, STATCOM, voltage regulator based on tap changer, or battery-supported inverter, was not identified in this research. Further studies are also needed.

5. Conclusions

Growing global electricity demand drives the development of renewable energy sources, including distributed energy and wind power plants. An increasing number of theoretical studies on the impact of wind power plants on grid performance appear in the scientific literature. Nevertheless, as shown in this paper, results obtained under laboratory conditions do not always reflect the performance of real generation systems. Field tests conducted by the authors on an actual wind power plant connected to a medium-voltage grid confirmed the positive impact of the source on the quality parameters of electricity transmitted through the power grid. According to the research carried out by the authors, all parameters determining the quality of electricity are maintained during the operation of a wind power plant. An increase in the power generated in the studied power plant decreased the value of the total voltage distortion coefficient THD_U and did not change the frequency level in the grid. The analysis showed that despite its advanced automation systems, the wind power plant under study significantly affects the voltage level at customers near the source, causing it to increase by approximately 2.5%. Particular attention should be paid to voltage fluctuations caused by an emergency wind turbine shutdown during the evening hours (when the grid voltage is lower than during the rest of the day). A sudden cessation of generation causes a 3% voltage fluctuation, which can affect equipment sensitive to rapid changes. Therefore, the proper diagnostics of generation equipment is particularly important both from the point of view of the stability of the power grid and the end user. It reduces additional negative factors, including those related to the threat of ensuring the continuity and safety of production and thus the profitability of production.

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