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POWER SYSTEMS AND POWER ELECTRONICS

Selected aspects of wind and photovoltaic power plant operation and their cooperation

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Abstract. The connection of renewable energy sources with significant nominal power (in the order of MW) to the medium-voltage distribution grid affects the operating conditions of that grid. Due to the increasing number of installed renewable energy sources and the limited transmission capacity of medium-voltage networks, the cooperation of these energy sources is becoming increasingly important. This article presents the results of a six-year study on a 2 MW wind power plant and a 1 MW photovoltaic power plant in the province of Warmia and Mazury, which are located a few kilometers away from each other. In this study, active energy, currents, voltages as well as active, reactive, and apparent power and higher harmonics of currents and voltages were measured. The obtained results show the parameters determining the power quality at different load levels. Long-term analysis of the operation of these power plants in terms of the generated electricity and active power transmitted to the power grid facilitated estimating the repeatability of active energy production and the active power generated in individual months of the year and times of day by a wind power plant and a photovoltaic power plant. It also allowed us to assess the options of cooperation between these energy sources. It is important, not only from a technical but also from an economic point of view, to determine the nominal power of individual power plants connected to the same connection point. Therefore, the cooperation of two such power plants with the same nominal power of 2 MW was analyzed and the economic losses caused by a reduction in electricity production resulting from connection capacity were estimated.

Key words: harmonic distortion; power quality; renewable energy sources.

1. INTRODUCTION

There are many reasons why renewable energy sources become increasingly popular and their share in the market increases at the cost of conventional sources based on hard coal, lignite, oil, natural gas, and radioactive elements. Renewable energy sources (RES), which include hydropower, solar power, wind power, geothermal energy, sea currents, tidal and wave energy, biofuel, biomass, biogas, and ocean thermal energy, have many advantages, but also disadvantages which fortunately can be minimized [1]. For example, power stations based on photovoltaic panels are not a fixed and rigid electricity source, since solar radiation determines the value of energy generated. Moreover, in the climatic conditions of many countries including Poland, it is subject to considerable seasonal changes. However, renewable energy sources will increasingly replace conventional coal power plants, especially following the approval of the European Union's zero-emissions strategy. The number of newly commissioned wind and waterpower plants has been limited due to some regulations [2–6], including the Act on Renewable Energy Sources [7, 8]. Nevertheless, these two types of renewable energy sources still draw attention as a means for balancing the demand for electricity in the power system and an alternative for coal power plants [9].

The selected aspects that are considered in the paper include the description of a PV power plant and a wind power plant followed by their energy production and power quality analysis as well as research on some advantages that may be brought by the cooperation of such plants connected to a common connection point. As the paper results show, a hybrid system consisting of a PV power plant and a wind power plant brings a new quality. The investigations devoted to hybrid systems are not so common as those dedicated to a single RES. Most of the papers on electricity generation and parameters determining the power quality of renewable sources are devoted either to photovoltaic power plants [10–17] or wind power plants [18–20]. The spectrum of the considered problems is wide. The paper [10] presents and discusses the results of measurements carried out on small-scale photovoltaic systems connected to a low-voltage grid, from the harmonic distortion point of view. The effect of reactive power compensation on system operation performance in grid-interactive cascaded PV systems has been analyzed in [11]. The other problem, addressed in [12, 14], consists of the optimal control algorithms of compensators used along with the PV systems. In [13], the analysis concerning the impact of the PV plant on the power grid in terms of the power quality

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included the results of active, reactive, and apparent power as well as higher harmonics of currents generated to power grids on the low-voltage side. A review of technical challenges due to the large-scale PV system penetration into the power system has been given in [15]. The survey conducted by the CIGRE working group [16, 17] has found that surprisingly there is a significant lack of information among utilities/network operators with respect to the possible impact of PV installations on power quality. On the other hand, modeling, and simulation techniques for studying the voltage fluctuation and harmonic distortion in a network to which variable speed wind turbines are connected, including some case studies, have been discussed in [18]. The analysis concerning the impact of the wind power plant on the power grid in terms of the power quality has been also shown in [19]. One of the most important problems consists in voltage fluctuations which have been studied in [20].

Some papers provide an analysis of the cooperation between these two renewable energy sources considering the problem on a small [21–31] or large scale [32–40] and showing the need for the optimization of such hybrid systems [41–44]. In [21], MATLAB/Simulink model and simulation of the effects of renewable technologies on the system performance have been investigated for various penetration levels and at different loading and weather conditions, indicating that severe power quality problems such as frequency and voltage fluctuations, voltage drop, harmonic distortion, and power factor reduction can occur. A separate analysis of power quality problems caused by wind and PV power stations has been carried out in [22, 28–30], while their accommodated capacity has been individually analyzed in [38]. The simulation results presented in [23] and even short-term measurements presented in [36] showed the complementary nature of wind and solar energy, especially regarding the output power variations from a photovoltaic power plant, a wind power plant, and their combination in a hybrid system. This paper allows us to draw, among others, a similar conclusion based on real long-term data (see Section 7). An analysis of a grid-connected hybrid PV-wind system from the economic point of view has been presented in [24, 26]. An interesting proposition of power quality problem solution for a hybrid system based on implementing additional functionality in a PV converter, which takes the role of a static synchronous compensator, has been presented in [25]. Modelling of hybrid systems and evaluation of the renewable energy accommodation capacity, which is important especially for system planners and operators to determine the suitable ratio of wind power and PV as well as renewable energy penetration ratio to take full advantage of renewable energy, have been shown in [27]. Our paper also presents the influence and costs of wind power and PV ratio, but this time based on long-term measurements (see Section 7).

The hybrid solution has also economic advantages and in the case of rural and remote areas may be an optimum solution [31]. The economic viability of PV power for wind systems has been assessed in [32, 35, 39] by the comparison of distinct simulation scenarios, which consider different rated power for each type of source. It has been also confirmed in [40], which shows that power demand is most effectively met by balanced configurations of wind and solar PV, while 100% wind or 100% solar PV configurations are less effective. In the case of Europe, if 100% energy production is based on RES, the optimal mix becomes 55% wind and 45% solar power generation [32]. For less than 100% renewable scenarios, a fraction of wind power generation increases, while that of solar power generation decreases. However, other studies [33] for northwestern Europe show that at the moment the optimal wind share is 20% and the variability dramatically impacts the optimal wind share (for constant winds it would be 60%). Another work [34] draws our attention to the problem of hybrid large-scale systems, namely, that commonly used control systems are designed for distributed single wind or PV power plants and may not be suitable for large-scale centralized clusters of wind and PV power plants. Therefore, it should greatly optimize the operation planning and active power regulation of renewable power by operating and controlling wind and PV power plant clusters as a whole. Moreover, due to the uncertainty of wind power and PV power output, more reserve and balance capacity is necessary in the case of large-scale wind power and PV power integration [36]. A review of the hybrid system has been presented in [45–47].

This study has been aimed to join the research streams described above. Its purpose is to analyze not only the operation of a single renewable source such as wind and photovoltaic power plants but, above all, the cooperation between these two sources of energy. The analysis aims to assess the possibility of cooperation between these two renewable energy sources based on actual measurements. The main contribution of this work compared to previous works consists in the detailed consideration of real data measured in wind and a PV power plant for 6 years. This case study allows us to draw reasonable conclusions about the repeatability of the RES as well as power quality issues. The energy production results can be generalized and used for many other locations in central Europe with similar weather conditions. As regards the impact of the RES on the grid, the results cannot be directly generalized because the impact depends on the grid conditions which may change a lot for different locations. The paper also includes an original analysis of the annual value of energy not generated to the grid due to connection capacity constraints resulting from some limits imposed on the energy that can be injected into the power network. As a result, the energy above the limit cannot be uploaded to the network, making the profit lower. At the stage of plant design, when the connection conditions are issued, distribution system operators (DSOs) make a power system analysis for the full generation capacity of the power plant. The analysis does not consider that due to weather conditions, solar and wind plants usually do not simultaneously generate maximum/nominal power. On the one hand, such an approach seems to be safer, but on the other, it limits more efficient usage of the connection capacity. The possibility of optimized use of the connection capacity was opened by Commission Regulation (EU) [48] (Article 14, point 2a and 2b). It gives DSOs the right to control the active power output, i.e. the power-generating module shall be equipped with an interface (input port) to be able to reduce the active power output following instruction at the input port, and the relevant system operator shall have the right to specify the requirements for further equipment to allow active power output to be remotely operated. The presented analysis may help to change the approach when analyzing the distribution network operation and as a result, may lead to optimized usage of connection capacity.

This paper is based on six years of measurements from two renewable energy sources, i.e. a 2 MW wind power plant and a 1 MW photovoltaic power plant. The power plants are a few kilometers away from each other. The measurements from both power plants were synchronized using GSM and GPRS data transmission. In the study, active energy, currents, voltages as well as active, reactive, and apparent power and higher harmonics of currents and voltages were measured (according to the standards [49–51]). It is a continuation and extension of previous works [13, 19] devoted to the individual analysis of renewable sources as well as their short- and long-term comparison made in [52]. With the share of renewable power generation increasing year by year, it will be even more important to take advantage of the two opposite behaviors of solar and wind power generation and their ability to counterbalance each other to a certain extent to follow the seasonal load curve. The best point of counterbalancing represents the seasonal optimal mix between wind and solar power generation.

The paper consists of eight sections with an introduction. Section 2 is devoted to the characteristics and rating data of the analyzed power plants. Section 3 presents the energy production from the photovoltaic power plant, while Section 4 presents aspects related to the parameters determining the power quality for the photovoltaic power plant. Sections 5 and 6 present an analysis of the operation of a wind power plant, with Section 5 presenting the production of energy from the wind power plant and Section 6 presenting the analysis of parameters determining the power quality. Section 7 examines the possibilities for cooperation between photovoltaic and wind power plants, in the context of a common connection point and the resulting constraints on the maximum active power generated to the grid. The paper ends with a discussion and conclusions.

2. CHARACTERISTICS OF A PHOTOVOLTAIC POWER STATION AND A WIND POWER STATION

The analyzed power plants are located near the town of Olsztynek (53.585968N, 20.277693E) in the province of Warmia and Mazury in north-eastern Poland.

The photovoltaic power plant is connected to the medium voltage MV grid via a 3×XRUHAKXS 120/50 mm^2 cable line, 9.6 km long, running from the Main Supply Point (MSP) with a voltage of 110 kV/15 kV. Two 16 MVA transformers are installed in the MSP. The transformers with short-circuit voltage equal to 12% work in parallel as spinning reserve. The short-circuit power on the MV side is equal to 141.4 MVA. On the premises of the photovoltaic power plant (Fig. 1), there is a container MV/LV station with an $S_N = 1000$ kVA transformer and an MV and LV switching station. Four thousand 250 W monocrystalline panels have been installed in the power plant. The data on photovoltaic panels are presented in [52]. The panels were connected to forty-six 20 kW inverters. Their data

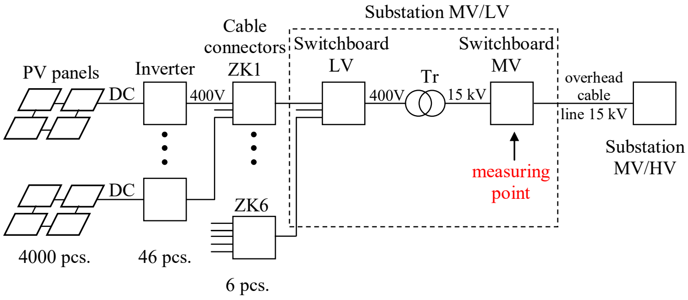

Fig. 1. Simplified diagram of the PV power station [39]

are presented in [13]. The total power installed is 1000 kW in the panels and 920 kW in the inverters. Inverters can therefore be temporarily overloaded by 8%. This situation will occur very rarely or not at all, due to the lower solar radiation intensity at this latitude and the significant influence of ambient temperature on the panel power (it decreases linearly along with the temperature increase [13]).

The wind power plant is connected to the medium voltage MV grid via a 3×XRUHAKXS 120/50 mm^2 cable line, 6.5 km long, running from the MSP with a voltage of 110 kV/15 kV. The station has two 16 MVA transformers with short-circuit voltage equal to 12% working in parallel as spinning reserve. The short-circuit power on the MV side is equal to 111.9 MVA. In the windmill, there is an asynchronous VESTAS V100 generator with a power of 2 MW and an MV/LV transformer station with a transformer with a power of $S_N = 2100$ kVA, MV and LV switching station (Fig. 2). The voltage and frequency supplied to the motor rotor (VCS – Vestas Converter System) as well as the inclination angle of the rotor blades facilitate controlling the power of the plant. The basic parameters of the asynchronous generator are given in [52], while the transformer data in [19]. Both MSPs supply urban-rural areas with some small and medium-sized enterprises.

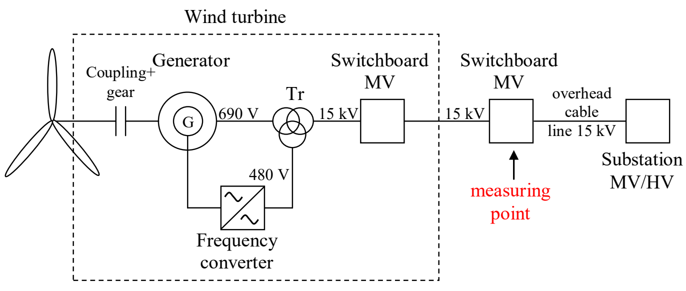

Fig. 2. Simplified diagram of the wind power station [50]

3. ENERGY PRODUCTION FROM THE PHOTOVOLTAIC POWER PLANT

The measurements show (Fig. 3) that the power plant did not reach the value of 1000 kW installed in the photovoltaic panels in any of the months. In the spring period, it approached the value of installed power in inverters. The fact that the top power

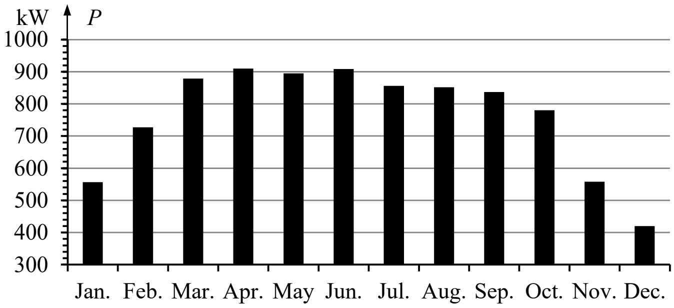

Fig. 3. The maximum active power (15 min. interval) generated by the PV power station in individual months (six-year maximum values)

values were achieved in April, May, or June is due to high sunshine and lower temperatures in those months, compared to the summer months. Therefore, at this latitude, the power installed in photovoltaic panels may be scaled by about 20% compared to the power installed in inverters. National regulations for the construction of photovoltaic power plants [2–8] and billing for renewable energy provide for the power installed in the panels as the basis for billing and verification of the power installed in the power plant as a whole. Therefore, it is necessary to review these provisions and clarify them by specifying the rated power of the power plant as not that resulting from the insolation (irradiation intensity) of 1000 W/m^2 but of 800 W/m^2. It will then be possible to use 100% of the connection power that was purchased from the power grid distributor. Many installed photovoltaic power plants with a nominal power of 1 MW resulted in significant underutilization of the transmission capacity of distribution grids in the MV network. According to the legal regulations (Energy Law) and building regulations (Construction Law), the active power of installed inverters may also be used as a basis for settlement and verification of nominal power. If the power of PV panels is higher than that of inverters, the latter limits the maximum active power generated to the power grid.

Active energy generated by a photovoltaic power plant is closely linked to the time of day, season, and place of installation. The value of energy produced in the winter months of November, December, January, and February does not exceed 20% of the value of energy produced in the summer months (Fig. 4). In these months, therefore, it is necessary to make

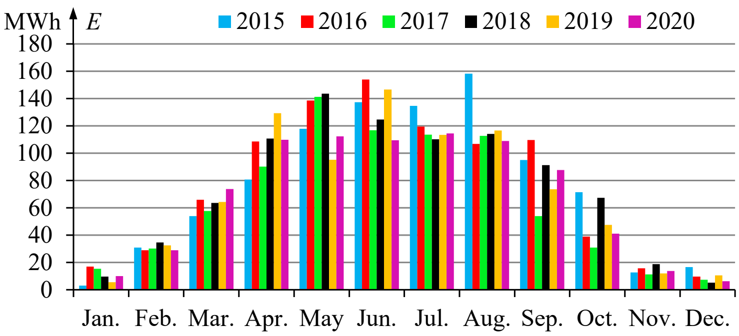

Fig. 4. Active energy generated by a photovoltaic power plant with an installed power of 1 MW in respective months

up for the lack of this energy in the system. On average, the photovoltaic power plant under consideration generates about 879 MWh of active energy per 1 MW installed in photovoltaic panels to the grid.

It is not only the season that affects the changes in active energy (active power) generated to the grid. These changes are also related to the time of day (Fig. 5). The median curve of changes in power generated to the grid has to be compared with the daily load curve of the distribution system. The typical load curve with morning and afternoon peaks deviates significantly from the generation curve of a photovoltaic power plant. Therefore, energy storage or other renewable energy sources should be used to compensate for production shortages in PV power plants.

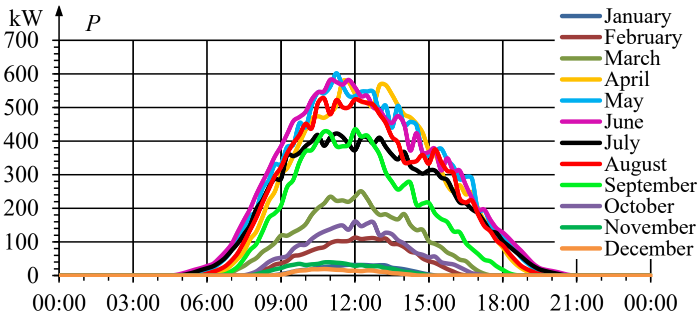

Fig. 5. Median of 6 years of active power generated by a 1 MW photovoltaic power plant in individual day quarters to the power grid, broken down into months

4. POWER QUALITY ANALYSIS FOR A PHOTOVOLTAIC POWER PLANT

Photovoltaic power plants should be designed in accordance with the standards IEC TS 62257-7-1:2010 [53], and their impact on the power system should not cause violating parameter thresholds given in the standard IEC TR 61000-3-6:2008 [54]. To examine the impact of the photovoltaic power plant on the MV power grid, the parameters determining the power quality in the substation on the medium and low voltage side were measured using a power quality analyzer (according to the standards [49–51]). The results of measurements on the LV side are presented in [13]. The voltage value on the MV side (Fig. 6) is only slightly dependent on the operation of the photovoltaic power plant and its power generation (Fig. 7). Much larger changes in the RMS voltage result from changes in the load of production plants and the associated changes in the position of the tap changer in the power supply transformer installed in the MSP. When the inverters operate, small amounts of inductive reactive power of the basic harmonic (Fig. 7) are taken from the mains, causing the power factor to be close to unity (Fig. 8). When the inverters operate in generation mode, the current is hardly deformed because the THD_I does not usually exceed 5% (Fig. 9). In the oscillations, some values are exceeding 5%, but only when the active power generated to the power grid drops. However, in such a case, the RMS value of higher harmonics

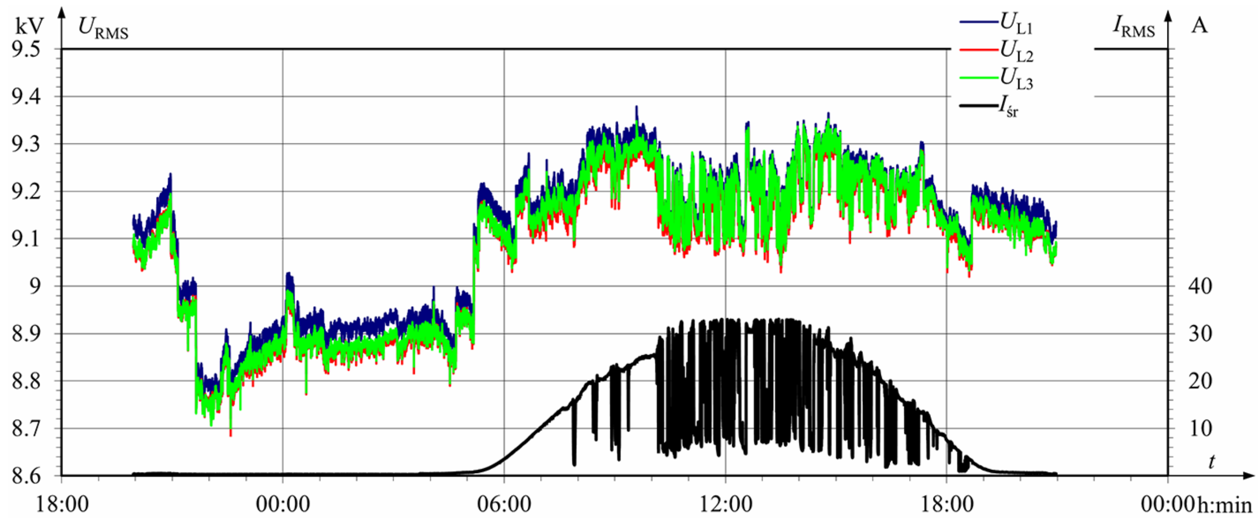

Fig. 6. Variations of RMS voltage on the MV side of the PV power station (L1, L2 and L3 denote phases) and average RMS current

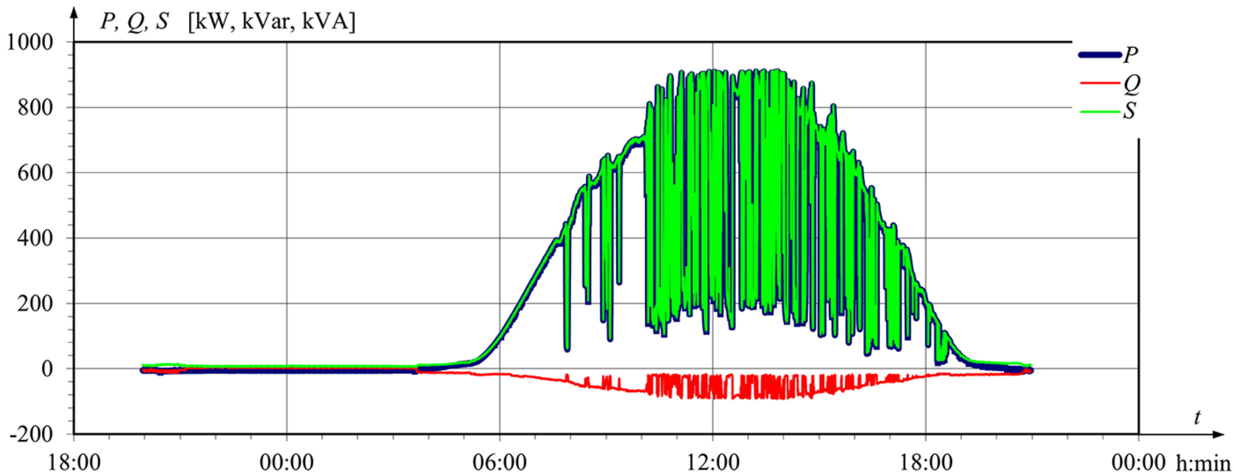

Fig. 7. Variations of the value of three-phase active, reactive, and apparent power generated by a photovoltaic power plant

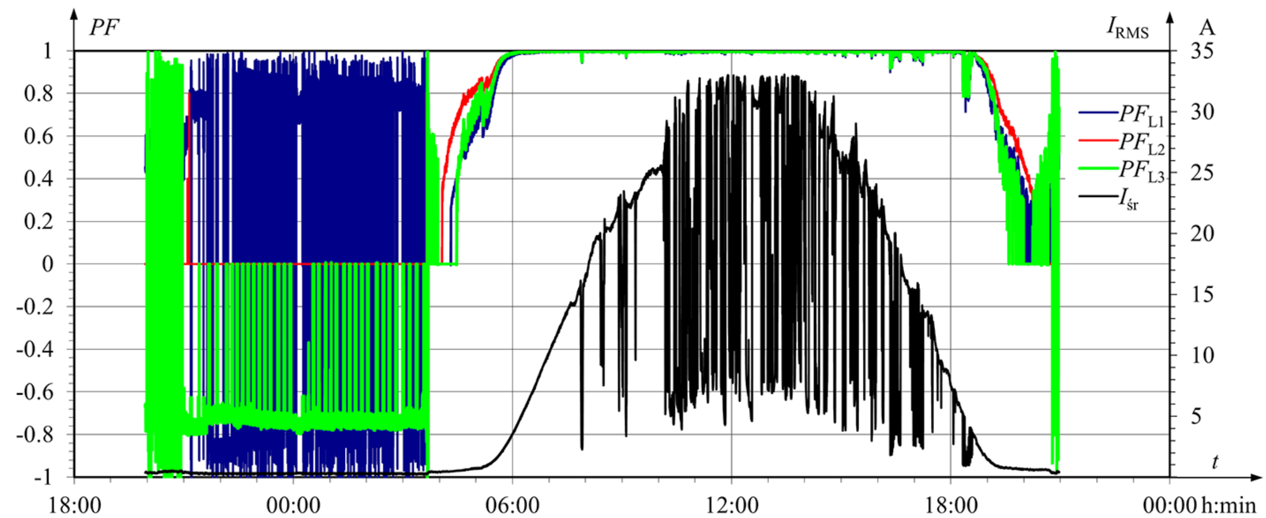

Fig. 8. Variations of the PV power plant power factor and average RMS current for one day

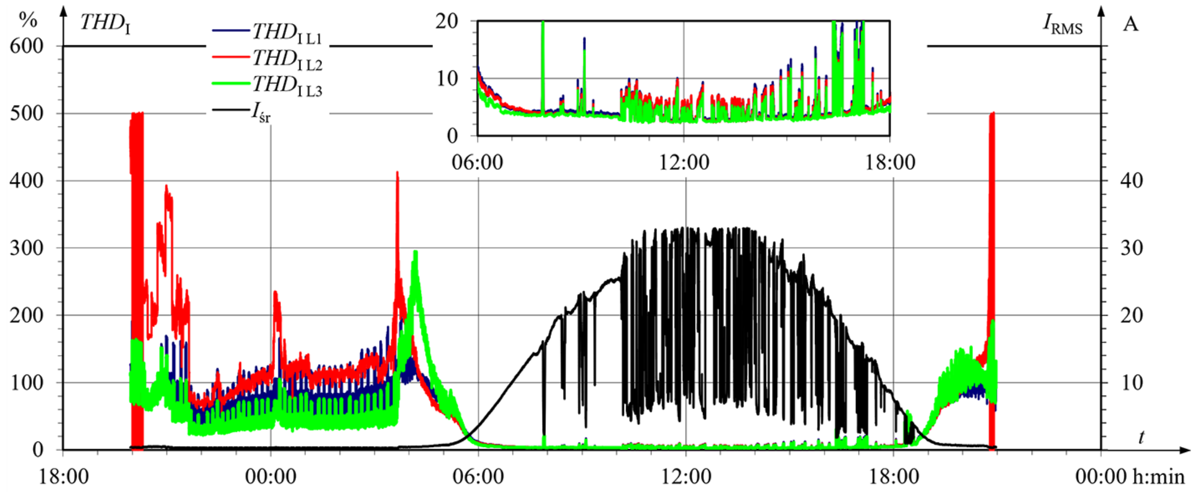

Fig. 9. Variations of the *THD* for currents generated by the PV power station on the MV side and average RMS current

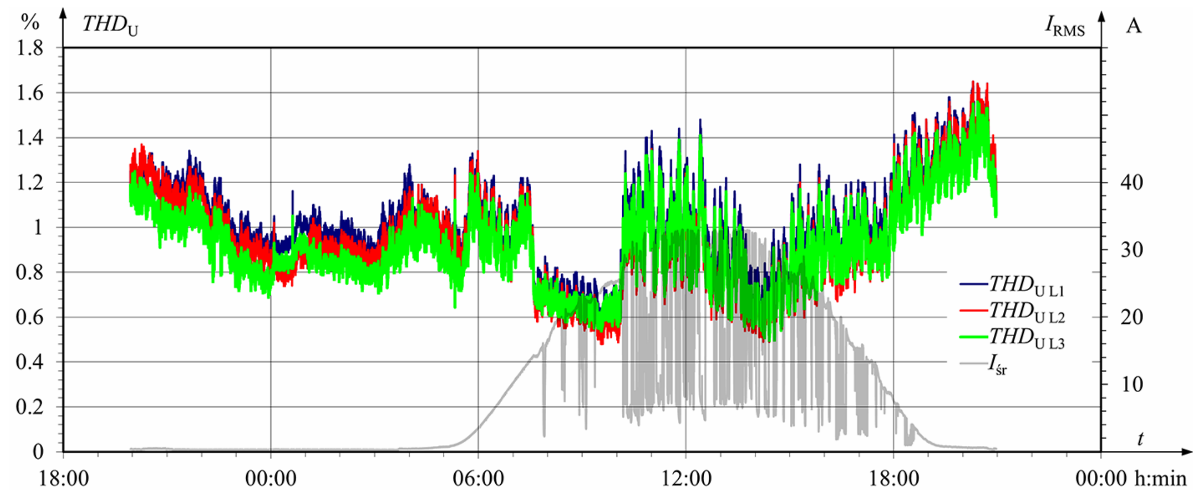

Fig. 10. Variations of the *THD* for voltages on the MV side and average RMS current

does not increase itself, but only their percentage value, due to the lower RMS value of the basic component. The power plant also does not influence the distortion of the THD_U supply voltage (Fig. 10). To precisely determine the influence of the power plant on the parameters determining the quality of generated current and supply voltage, THD_I (Fig. 11) and THD_U (Fig. 12) have been juxtaposed as a function of the load degree of the photovoltaic power plant. The results show that a decrease in the power generated to the grid results in increasing the current distortion. On the other hand, a change in the power generated to the grid has little effect on the distortion of the supply voltage. In the range of 20–90% of the power generated in a power plant, the THD_U value changes little. With a load below 20%, a clear increase in the percentage of higher harmonics in the

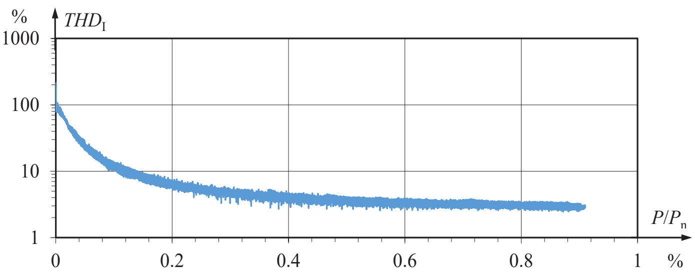

Fig. 11. Variations of the *THD* for currents generated to the power grid depending on the level of load (P/P_n) to the photovoltaic plant

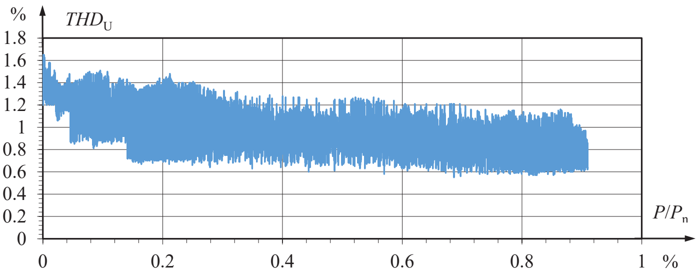

Fig. 12. Variability of the *THD* for voltage in the medium voltage grid depending on the level of load (P/P_n) to the photovoltaic plant

supply voltage is observed. The measured values of the power quality parameters are consistent with the requirements of the standards [54, 55] and regulations [2–8].

5. ENERGY PRODUCTION FROM A WIND POWER PLANT

The energy generated by the wind power plant in individual months of the year has been presented in Fig. 13. The analysis of the figure shows that the energy generated from May to September is on average twice as low as in the other months. Moreover, additional analysis has been carried out to get insight into the daily changes of the power generated to the grid for each of the months. The active power median for individual times and months has been presented in Fig. 14. The analysis shows that in the daytime, from 9 a.m. to 6 p.m., a wind power plant generates much less electricity. This is particularly visible in summer and spring (Fig. 14b). In summer, the active power generated to the grid during the daytime decreases by half. From a year-average perspective, a wind power plant generates about 3 GWh of active energy to the grid per 1 MW of installed power.

6. POWER QUALITY ANALYSIS FOR A WIND POWER PLANT

Wind power plants should be designed in accordance with the standards IEC 61400-21-1:2019 [56], and their impact on the power system should not lead to the violation of parameter thresholds given in the standard IEC TR 61000-3-6:2008 [54]. To estimate the influence of the wind power plant on the power grid, some power quality parameters were measured. Out of a few weeks of measurements on the medium voltage side, two representative days, on which the turbine operated from the minimum value (0 MW) to the maximum value (2 MW), were selected. The voltage measurements on the MV side presented in [50] show that the active power generated to the grid does not influence the grid voltage, which depends rather on the facilities connected to this grid. The variability of active power has been presented in Figs. 15 and 16. It can be noticed

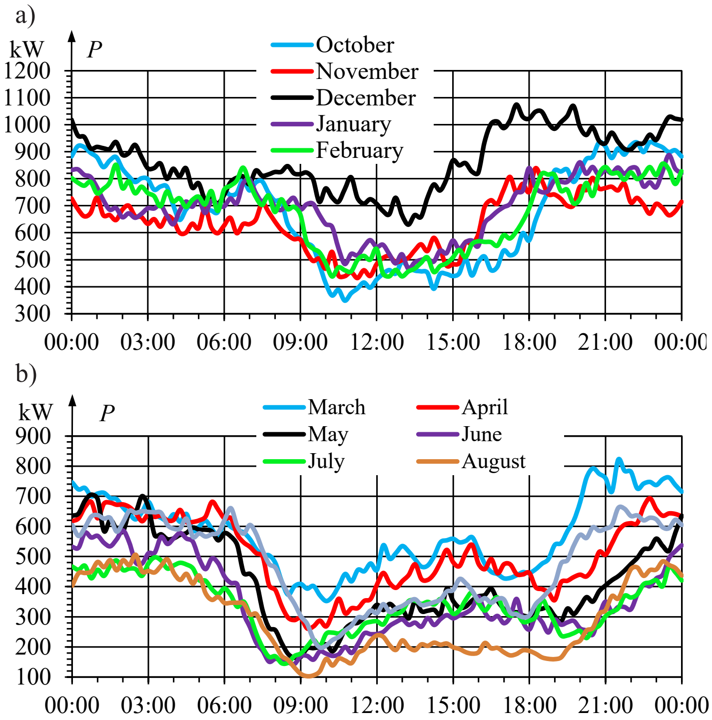

Fig. 14. Median of 6 years (2015–2020) of active power generated by a wind power plant in individual day quarters to the power grid, broken down into months

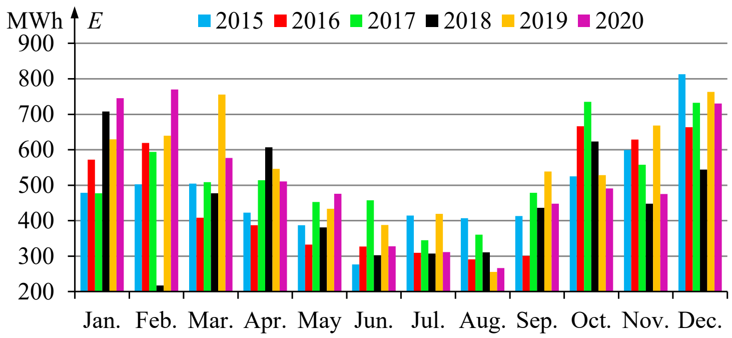

Fig. 13. Active energy generated by a wind power plant with an installed power of 2 MW in respective months

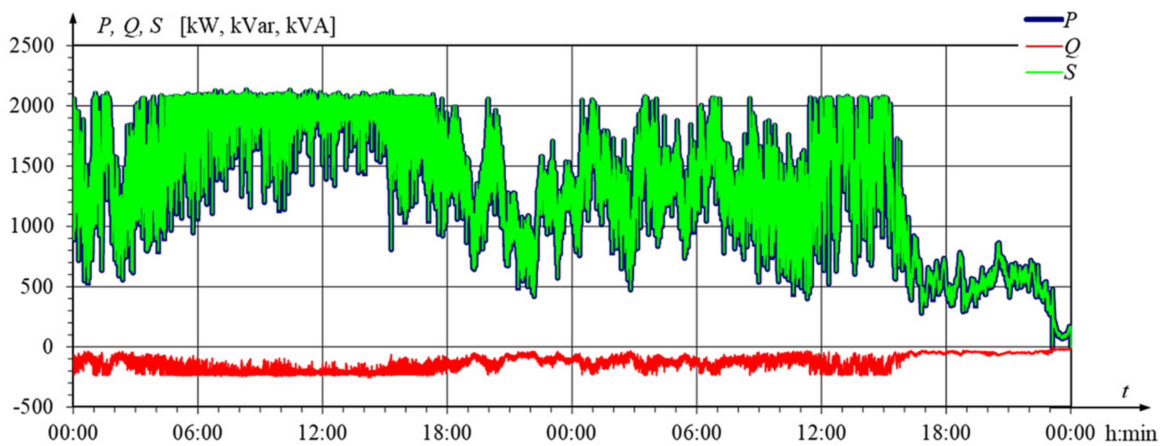

Fig. 15. Variations of three-phase active, reactive power of the fundamental harmonic and apparent power generated on the MV side to the power grid

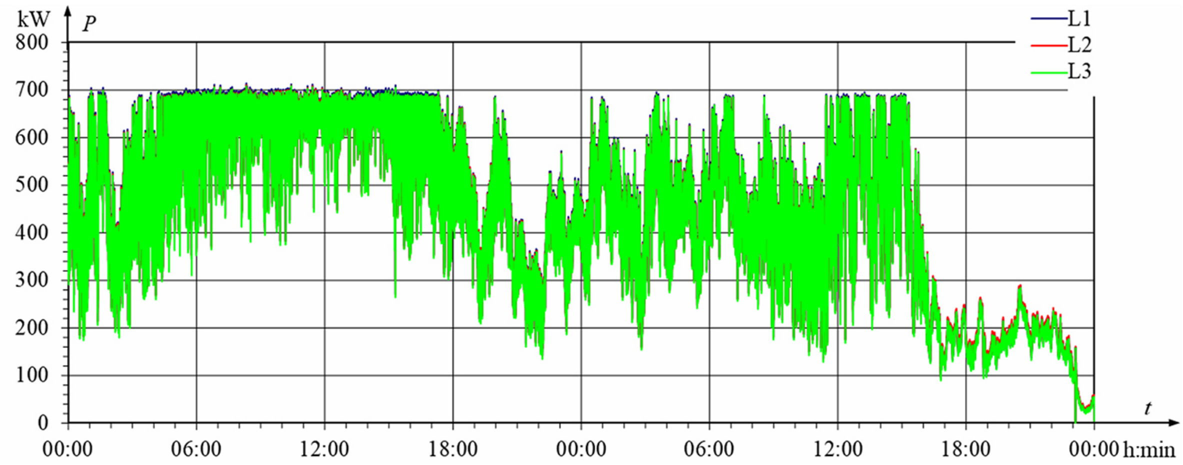

Fig. 16. Variations of active power generated by the wind power plant

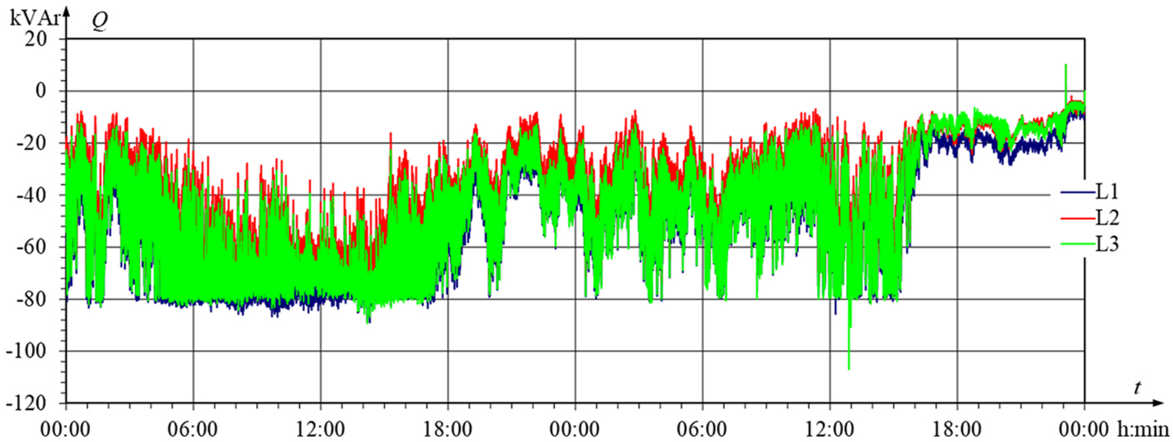

Fig. 17. Variations of reactive power of the fundamental harmonic generated by the wind power plant

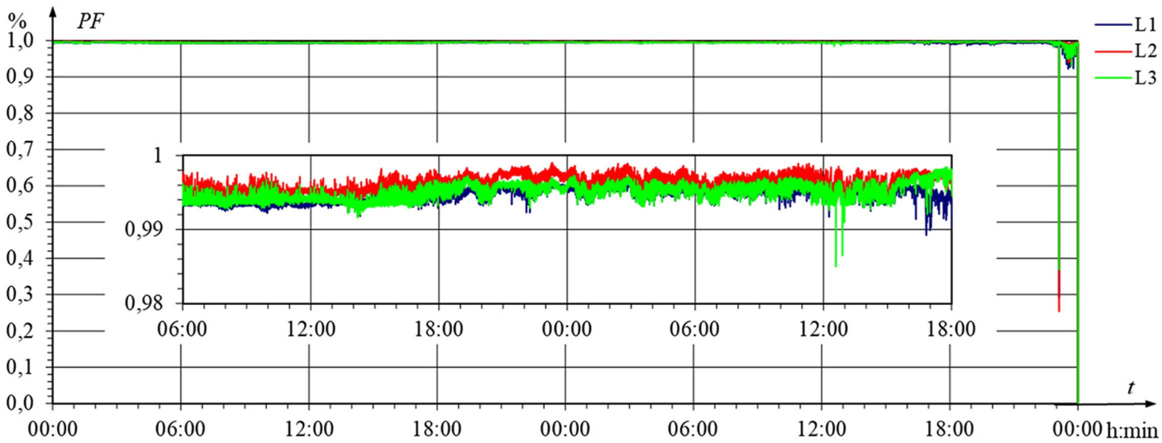

Fig. 18. Variations of the power factor of the load drawn by the wind power plant

(see Figs. 15 and 17) that the reactive power of the fundamental harmonic follows the changes in the active power and the power factor (Fig. 18) is close to one except for periods when the active power generated to the power grid is low. The consumption of the reactive power which can be noticed in Fig. 17 for a very short time is related to the capacity of the turbine supply cable, and not to the operation of the turbine itself. The measurements of higher harmonics of currents generated by the wind power plant on the MV side during normal operation indicate that the relative value of individual harmonics related to the first harmonic does not exceed 2% – see Fig. 19. It is not true only for periods when the generated power (current RMS value) is low – see Fig. 20. In that case, the THD_I coefficient can reach such high values as 30% and even more. The time waveforms of distorted currents generated to the grid during the start-up of the generator, i.e. when the active power is low, can be found in [50]. The values of individual harmonics, both odd and even, in the load current (Fig. 21) usually do

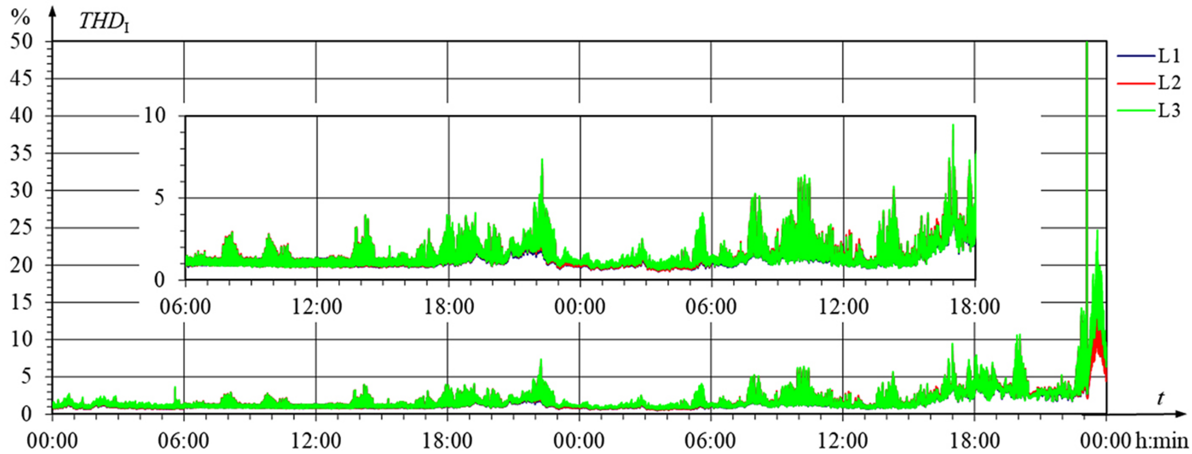

Fig. 19. Variations of *THD* for currents generated by the wind power plant on the MV side

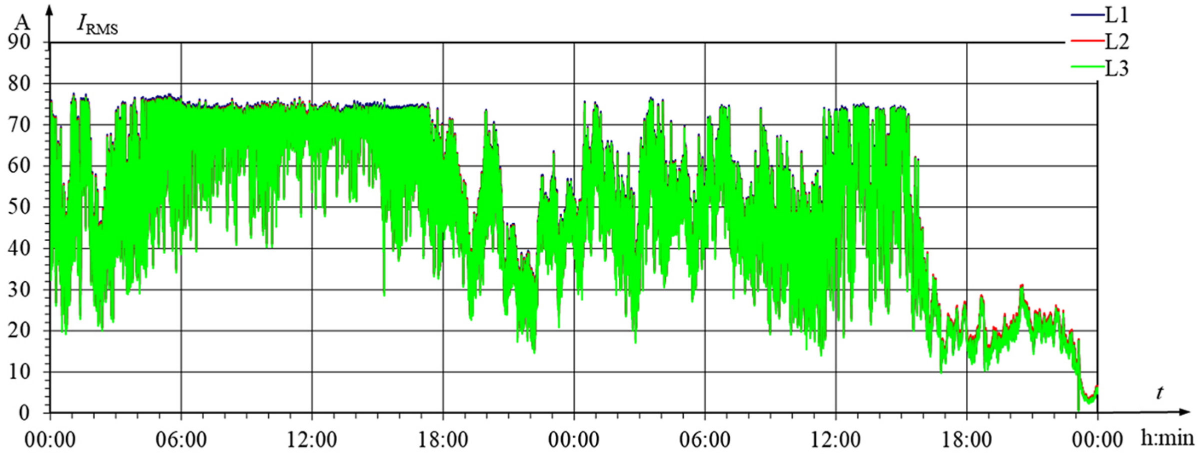

Fig. 20. Variations of the RMS current on the MV side of the wind power plant

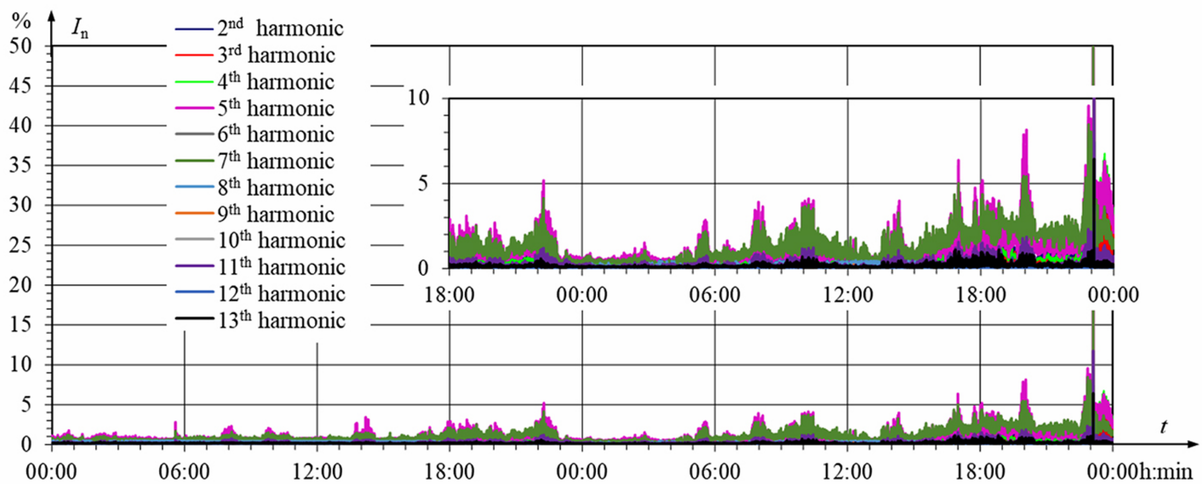

Fig. 21. Variations of higher harmonics of currents generated by the wind power plant on the MV side

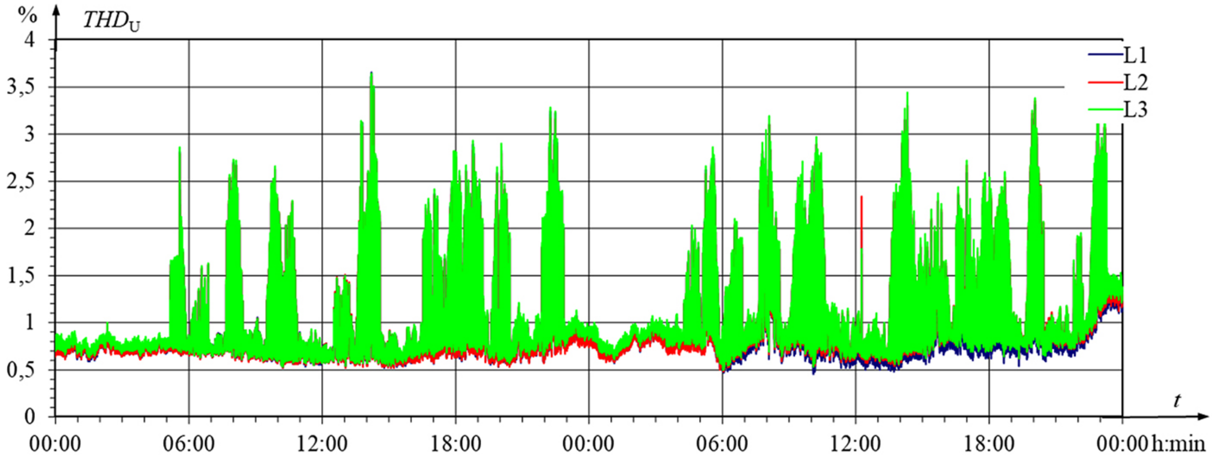

Fig. 22. Variations of higher harmonics of voltages on the MV side

not exceed 10%. The wind power plant does not cause voltage distortion in the medium voltage grid to which it is connected (Fig. 22). The value of the supply voltage *THD* coefficient does not exceed 1.5% for most of the observation period and exceeds 3.5% only for a very short time. The value of both individual harmonics and the total content of higher harmonics in the supply voltage do not exceed the limits specified in the standard [55]. Like in a photovoltaic power plant, to precisely determine the influence of the power plant on the parameters affecting the quality of generated current and supply voltage, THD_I (Fig. 23) and THD_U (Fig. 24) have been juxtaposed as a function of the load degree of the wind power plant. THD_I

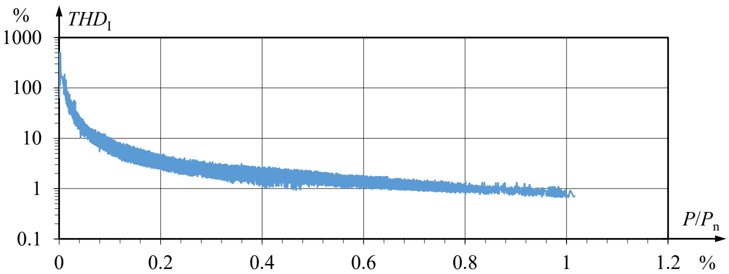

Fig. 23. Variations of the *THD* for currents generated to the power grid depending on the level of load (P/P_n) to the wind power plant

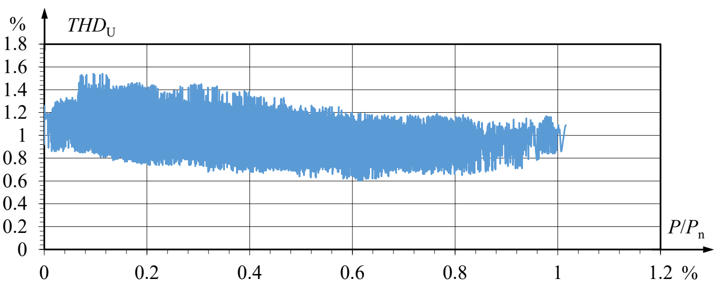

Fig. 24. Variability of the *THD* for voltage in the medium voltage grid depending on the level of load (P/P_n) to the wind power plant

results are similar to a photovoltaic power plant. A decrease in the power generated to the grid results in increasing current distortions. On the other hand, a change in the power generated to the grid has little effect on the distortion of the supply voltage. As the power generated to the grid decreases, a minor percentage increase of the content of higher harmonics in the supply voltage is observed. The measured values of the power quality parameters are consistent with the requirements of the standards [54, 55] and regulations [2–8].

7. ANALYSIS OF COOPERATION BETWEEN A PHOTOVOLTAIC POWER PLANT AND A WIND POWER PLANT

The analysis of the active energy generated by a photovoltaic power plant presented in Section 3 (Fig. 4) and the analysis of the active energy generated by a wind power plant presented in Section 5 (Fig. 13) both show that in winter and autumn periods a photovoltaic power plant generates very small amounts of electricity, while a wind power plant generates high amounts of active energy. Therefore, a photovoltaic power plant should be connected to the same connection point as a wind power plant. Smaller fluctuations of energy generated to the grid over individual months would then be achieved (Fig. 25). The

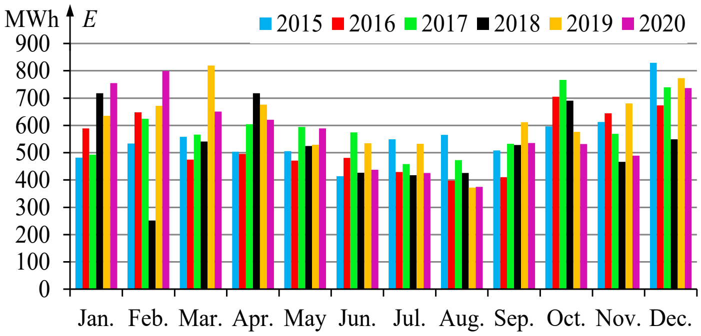

Fig. 25. Total energy produced from a 2 MW wind power plant and a 1 MW photovoltaic power plant

results obtained indicate that once these power plants were connected to the grid, the decrease in active energy generated in the summer period was significantly reduced. Both of these power plants complement each other. Since the connection of these power plants to a common connection point may result in exceeding the limit value of the power generated to the grid through exceeding the connection capacity, the operation of these power plants in minute-long intervals was analyzed over the whole day over 6 years. The six-year median active power generated by a photovoltaic power plant (Fig. 5) with a nominal power of 1 MW in individual day quarters shows that the energy is produced in the period in which the wind power plant generates significantly less active power to the grid (Fig. 14). On average (median value), the connection of these power plants does not cause the connection capacity of the wind power plant to be exceeded, and significantly reduces the power shortage between 9 a.m. and 6 p.m. especially in the summer months (Fig. 26). If the connection power is increased, it is possible to reduce the power generated in the wind turbine by changing the inclination angle of rotor blades, or reducing the power generated from PV inverters, appropriately controlling the inverter. As the measurement results were synchronized, how much energy that would not be produced when the two power plants are connected to one connection point was analyzed due to the constraints resulting from the connection capacity (Fig. 27). In accordance with the agreements between power network operators and the RES energy providers, there are some limits imposed on the energy which can be injected to the power network. The technical constraints are the main reason which makes these limits, and they are summarized by the connection capacity. As a result, the energy above the limit cannot be uploaded to the network – we can say it is lost and makes the profit lower. The annual value of energy not generated to the grid due to connection capacity constraints is shown in Table 1 and Fig. 28. The analysis has been made for connection capacity ranging from 1.8 MW to 2.5 MW to show that increasing the connection capacity decreases the energy not generated to the network. The annual value of energy not generated for this reason is approximately equal to 0.5% of the total active energy production from the wind power plant with a limitation to 2 MW, i.e. the same power as the wind power plant itself.

Since the power plants under analysis are not identical in terms of installed power, to make the comparison of energy production more objective, energy production with the same

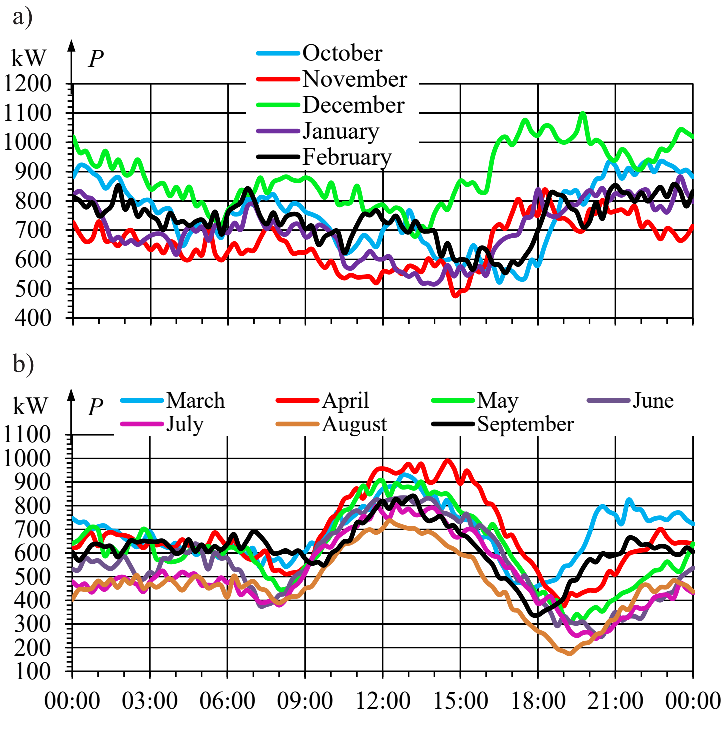

Fig. 26. Median of 6 years of active power generated by a 1 MW photovoltaic power plant and a 2 MW wind power plant in individual day quarters to the power grid, broken down into months

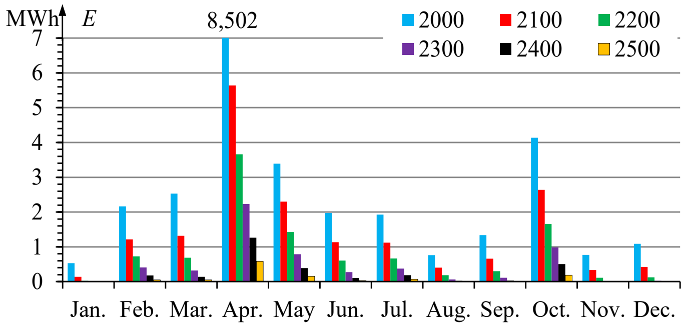

Fig. 27. The 6-year average of energy not generated to the power grid due to connection capacity constraints (ranging from 2000 kW to 2500 kW) in individual months of the year depending on the value of connection capacity for the combined 2 MW wind power plant and 1 MW photovoltaic power plant

Table 1
The 6-year average of energy not generated to the power grid due to connection capacity constraints depending on the value of connection capacity for the combined 2 MW wind power plant and 1 MW photovoltaic power plant and the combined 2 MW wind power plant and 2 MW photovoltaic power plant

Connection capacity	Value of energy not generated to the power grid for the combined 2 MW wind power plant and 1 MW photovoltaic power plant	Value of energy not generated to the power grid for the combined 2 MW wind power plant and 2 MW photovoltaic power plant
1800 kW	136.9 MWh	262.5 MWh
1900 kW	70.2 MWh	176.4 MWh
2000 kW	31.0 MWh	119.4 MWh
2100 kW	19.4 MWh	91.3 MWh
2200 kW	12.4 MWh	70.2 MWh
2300 kW	7.9 MWh	53.7 MWh
2400 kW	5.2 MWh	40.8 MWh
2500 kW	3.6 MWh	30.8 MWh

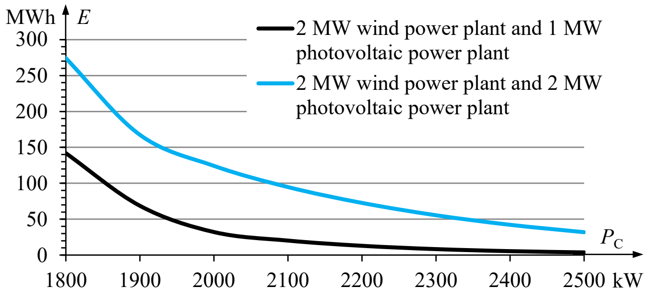

Fig. 28. The 6-year average of energy not generated to the power grid in a year due to connection capacity PC constraints depending on the value of connection capacity for the combined 2 MW wind power plant and 1 MW photovoltaic power plant and the combined 2 MW wind power plant and 2 MW photovoltaic power plant

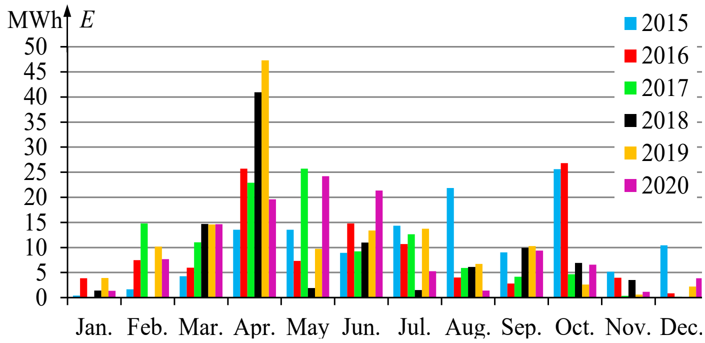

Fig. 31. Energy not generated to the power grid with combined 2 MW wind power and 2 MW photovoltaic power plant due to the connection capacity constraint to 2 MW in individual months of the year

installed power, i.e. 2 MW, was also analyzed. The energy generated to the grid by the photovoltaic power plant would then be as in Fig. 29. The total active energy generated to the power grid by both power plants, with an installed power of 2 MW each, would reach a value even more stable over individual months than in the case of 2 MW + 1 MW (wind power plant + PV power plant) – see Fig. 30. The energy not generated to the grid due to the connection capacity constraints to 2 MW will be most pronounced in April (Fig. 31).

The median active power generated by the 2 MW photovoltaic power plant itself is shown in Fig. 32. The analysis shows that, at its peak, the power plant generates on average up to 1300 kW of active power. However, after connecting it to a wind power plant, the maximum value of the median power in the summer months reaches 1.6 MW and 1.7 MW in March and April (Fig. 33). When a photovoltaic power plant is connected

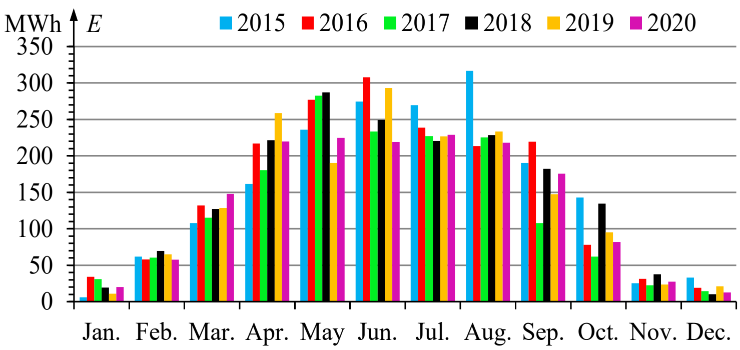

Fig. 29. Energy produced from a PV power plant with an installed power of 2 MW

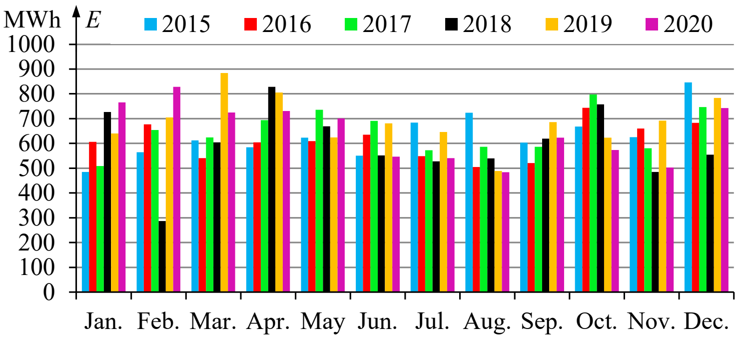

Fig. 30. Total energy produced from a 2 MW wind power plant and a 2 MW photovoltaic power plant

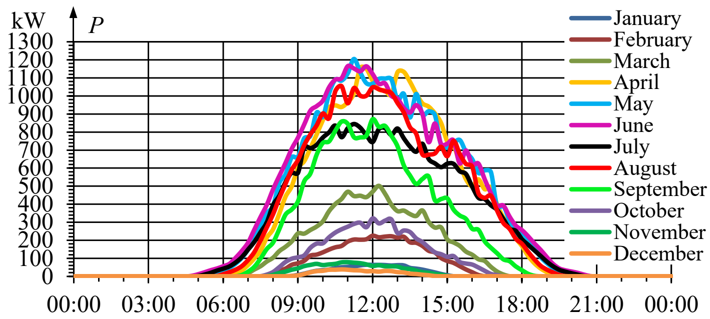

Fig. 32. Median of 6 years of active power generated by a 2 MW photovoltaic power plant in individual day quarters to the power grid, broken down into months

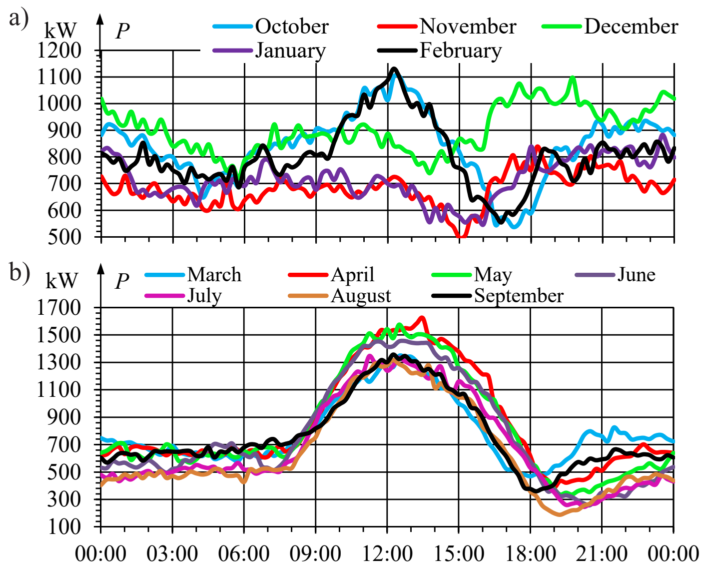

Fig. 33. Median of 6 years of active power generated by a 2 MW photovoltaic power plant and a 2 MW wind power plant in individual day quarters to the power grid, broken down into months

to a wind power plant with a power of 2 MW each, the peak of active power generation to the grid occurs between 8 a.m. and 5 p.m. This curve partly coincides with the daily load curve, as most plants operate during these hours. Compared to the previous proportions between the photovoltaic and wind power plants, a significant increase in energy not generated to the grid due to connection capacity constraints was recorded (Fig. 34). The annual value of energy not generated to the grid due to capacity limitation amounts to approximately 2% of the total active energy production from a wind power plant with a limitation to 2 MW (see Table 1 and Fig. 28). Thus, it is a small loss in relation to the profits resulting from the additional power installed in the system, but it is 4 times higher than in the case of the connection of the 2 MW wind power plant and the 1 MW photovoltaic power plant. Increasing the connection capacity diminishes the energy not generated to the network in a similar way to the previous case.

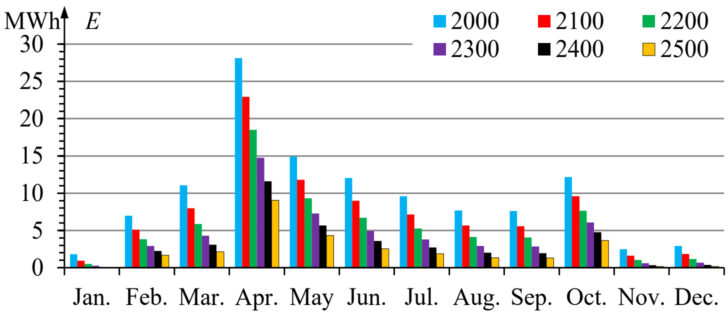

Fig. 34. The 6-year average of energy not generated to the power grid due to connection capacity constraints in individual months of the year depending on the value of connection capacity for the combined 2 MW wind power plant and 2 MW photovoltaic power plant

8. CONCLUSIONS

The analyzed power plants are located in the Warmia-Masuria Province in north-eastern Poland. Therefore, in our opinion, the presented exemplary results are not very specific and representative for only one location. In fact, the environmental conditions (regarding the main wind direction and speed as well as sun radiation) are very similar in large areas, in our case located not only in Poland but also in central Europe. The results presented in the paper can be useful when estimating future energy production as well as costs and income for similar locations. As a result, taking a preliminary decision about the location of power plants based on renewable energy sources should be also simplified. Nevertheless, the location of power plants based on such sources always requires individual analysis.

This paper discusses the impact of the operation of a photovoltaic and wind power plant on the power grid. Both power plants have similar power and are connected to the medium-voltage grid using cable lines of several kilometers in length, supplied by 110 kV/15 kV stations. These power plants are a few kilometers away from each other, which has facilitated a reliable comparison of their operation in real-time, especially since the measurements were taken over six years and were synchronized with the GSM network. For data size reasons, six-year power and energy measurements were limited to 15-minute intervals. Detailed measurements of active, reactive, and apparent power, as well as higher harmonics of currents and voltages, were made in one-second intervals. Due to the overwhelming amount of data from one-second measurements, measurements were presented for two days only.

Both power plants under investigation exhibited repeatable results of active power and active energy generated to the grid over six years. It is thus possible to estimate the amount of energy produced in monthly and annual cycles, as well as during the individual times of the day. A wind power plant generates the most energy during the autumn-winter period. In late spring and summer, the value of active energy generated to the grid decreases by about a half. In turn, the photovoltaic power plant generates the most energy to the grid during the spring-summer period. Due to the character of the operation of a photovoltaic power plant, i.e. generation limited to the daytime, this power plant generates yearly about 0.88 GWh per 1 MW of installed power in the panels, whereas a wind power plant generates about 3 GWh per 1 MW of installed power in the generator. Nevertheless, the photovoltaic power plant can very well supplement the energy not produced by the wind power plant between May and September. With a photovoltaic power plant with an installed power equal to that of a wind power plant, the total energy generated to the grid in individual months (Fig. 30) would exhibit little variability and would fluctuate in the 150 MWh range oscillating around 640 MWh per month. With such a proportion of power installed in the power plants and with 2 MW constraints on the active power generated to the grid, the investor would annually lose about 122 MWh of active energy not generated. Considering electricity prices at the level of about EUR 100 per MWh, the loss would reach EUR 12200, which is about 2% of the active energy produced from the wind power plant alone or 7% of the active energy produced from the photovoltaic plant alone. Given that the energy measurements were averaged over 15 minutes, the loss of energy not generated would be greater, but even if the analysis error is 100% more than calculated, a loss of 4% of the energy produced from the wind power plant still presents a meaningful result. Thus, legal regulations should be amended to make easier the construction of new wind turbines in existing photovoltaic plants by connecting them to common connection points. Such regulations would facilitate not only the construction of these power plants but also the form of settlement with the Energy Regulatory Office (URE), which supervises the energy transformation in Poland. Connecting these power plants at a single connection point to the power grid will result in better use of the transmission capacity in the distribution networks and accelerating energy transformation in Poland in a way that does not require extensive construction costs or time-consuming investments.

Combining a photovoltaic power plant with a wind power plant improves the conditions for generating power during the daytime. A wind power plant generates active power to the grid throughout the day. However, the highest values of the active power median are observed at night. This is particularly visible in spring and summer. Then, from 8 a.m. to 6 p.m. or 7 p.m., a significant drop in the power generated to the grid is observed, even by half (Fig. 14b). In turn, a photovoltaic power plant generates active power in these hours. Once these power plants are connected to the grid, the active power generated during this period of the day reaches its highest value (Fig. 33). This is advantageous for the daily load curve, where the active power drawn from the grid during the daytime is the highest.

An analysis of the parameters determining the power quality for a photovoltaic power plant showed that it has little impact on the parameters determining the power quality. When the inverters operate in generation mode, the current generated to the grid contains higher harmonics of currents of negligible value, i.e. THD_I less than 5%, and the content of higher harmonics of voltage on the medium voltage side is then on average less than 1.6%, with local peaks up to 20%. However, the content of higher harmonics in the supply voltage on the medium voltage side does not exceed 1.8% and no influence of the photovoltaic power plant on its value was observed over its course. In addition, no negative impact on the content of higher harmonics in the generated current was observed during the operation of the wind power plant. Maximum values up to 10% are observed with small amounts of power generated to the grid. For powers of 20% of the rated power, the higher harmonics in the current do not exceed 3%. In the supply voltage on the MV side, the higher harmonics are also up to 1.5%, with peaks of up to 3.5%, which are not associated with this wind power plant. As shown in Figs. 12 and 24, the negative impact of photovoltaic and wind power plants on the parameters determining the quality of the supply voltage, especially on the THD_U value, is very small. The generation of current with a higher content of higher harmonics by both power plants occurs at very low values of power generated to the grid (Figs. 11 and 23). Their impact on the grid will largely depend on the quality and structure of the supply network, i.e. the length of the line, the impedance of the line and supply system, and the number of photovoltaic and wind power plants connected to the grid in one region.

The analyses of the operation of photovoltaic and wind power plants presented in this paper indicate a lack of (or very insignificant) impact of these renewable sources on the parameters determining the power quality at the medium voltage level. The measurements of higher harmonics of currents and voltages generated by the wind power plant and the PV power plant on the MV side indicate that, during normal operation, the content of individual harmonics does not exceed 2%. The situation changes with lower values of currents generated to the grid, but due to the low power generated, its influence on the network is negligible. As a result, the value of the THD coefficient for the supply voltage does not exceed the permissible values specified in the standards.

The analysis of the levels of active power generated to the power grid indicates their high sensitivity to weather conditions, not only in the short-term but also in the long-term perspective. Nonetheless, some repeatability in the generated active power to the power grid can be observed both in the short term (daily) and the long term (annually). It means that the wind generation and sun radiation patterns are to some extent similar over the years. Combining these two renewable sources has a positive impact on the average value of the energy generated in each month of the year. In the short term, i.e. a daily perspective, their combination also has a positive impact on the power generation curve. The best results for the long-term as well as short-term energy production are achieved by combining power plants with the same nominal power, despite large differences in the total (annual) energy generation by individual power plants (wind 3 GWh/year per 1 MW installed power and photovoltaic 0.88 GWh/year per 1 MW installed power). With the power plants connected in this way, the connection capacity of a single power plant to a single connection point may remain unchanged and the financial losses resulting from the electricity not produced will not exceed 2% of the total energy produced from these power plants. Construction of power plants connected in this way will not only result in creating a permanent source of power (both in long-term and short-term perspective) but will also reduce the need for costly construction of new or modernization of old MV power lines, which requires several years. Of course, such a hybrid system will also require energy storage, but the storage capacity and, consequently, the cost can be minimized.

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