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THE IMPACT OF WIND FARMS ON ACTIVE POWER LOSSES IN THE POWER SYSTEM

Increasing emission standards and European Union policy require investment in the renewable energy sector. An increasing amount of renewable energy sources, including wind farms, requires changes in the power system in countries whose energy is based on large system power plants, mostly coal-fired. Stricter share of renewable energy sources in energy mix, may improve the country's security and ensure the diversification of fuels and the gradual independence of conventional fuels. Thanks to regulation possibilities of doubly-fed induction generators, which are equipped with a significant part of wind turbines, it is possible to obtain better electricity parameters. The location of energy sources near the receiving nodes has a positive effect on the active power losses in the power system. This article analyzes the impact of a 30 MW wind farm on the level of active power losses in the power system, taking into account the different power factor values with which the wind farm can work. Simulation were carried out using the Powerworld Simulation software.

Keywords: wind farm, power system, active power losses

1. Introduction

The development of civilization is the cause of the growing demand for electricity [1]. The prospect of depletion of natural energy sources such as coal, gas and oil makes it necessary to search for new energy sources and increase the share of alternative energy sources based on renewable resources. As a result, renewable energy sources account for an increasing share of electricity production [2]. According to data prepared by the Polish National Energy Conservation Agency, electricity consumption in Poland will increase from 165.8 TWh in 2017 to nearly 230 TWh by 2040 [3]. According to this report, the share of renewable energy sources will increase to about 33%, the share of coal will fall to 33%, while the remaining 34% will go to nuclear, natural gas and lignite.

Wind and photovoltaic power plants are among the most popular sources of electricity coming from renewable sources in Poland. According to data from the Polish Energy Regulatory Office [4], in 2018 the total installed capacity in wind

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power plants amounted to 5 874.778 MW, which accounted for 68.43% of the installed capacity in renewable energy sources in Poland.

A large number of wind farms connected to the power system has an impact on the level of active power losses in the power system [5]. The paper presents the analysis of active power losses in a given fragment of the power system depending on the reactive power generated, to which a wind farm consisting 10 wind turbines has been connected. Simulation were carried out using the Powerworld Simulator, which enables to analysis of the active and reactive power distribution.

2. Active power losses in transmission lines

Active power losses are associated with any process of generation, transmission and use of electricity [6,7]. Active power losses in the power system can be divided into load losses, which depend on the load and no-load losses, which in practice don't depend on the load. The general formula for active power losses can be represented by equation:

$$P = \int_V J^2 \rho dV \tag{1}$$

where: J – current density, ρ - conductive material resistivity, V – volume of the conductive element.

In the case of a homogenous track of which the cross-section is constant:

$$P = I^2 R \tag{2}$$

where: I – current, R – resistance.

The active power losses associated with transmission line load can be calculated using the equation [8]:

$$\Delta P_L = 3I^2R = 3\left(\frac{S}{\sqrt{3}U}\right)^2 R = \frac{S^2}{U^2}R = \frac{P^2 + Q^2}{U^2}R \tag{3}$$

where: S – apparent power, Q – reactive power, U – phase to phase voltage.

No-load losses of active power shall be determined for network element in which the substitution schemes take into account the conductance. No-load losses can be calculated using the equation:

$$\Delta P_j = U^2 G \tag{4}$$

where: G – conductance of the network element.

Resultant active power losses can be determined by the equation:

$$\Delta P = \Delta P_L + \Delta P_j \tag{5}$$

3. Analysis of active power losses in the power grid

Simulations of active power losses were carried out for a wind farm consisting of 10 Vestas V90 - 3 MW wind turbines (WT1-WT10). Figure 1 shows the relation between active and reactive power of the analyzed wind turbines with doubly-fed induction generators [9,10, 11]. The 30 MW wind farm was connected to the 110 kV power system. The designed wind farm will have a radial structure. The wind farm consists of three radial lines connected to the main power supply point located on the area of the wind farm. In the case of a radial structure, damage to the cable stops the transmission of energy from the wind turbines located behind the damaged part of the internal grid. Greater reliability is characterized by a loop system, which in the event of a cable failure does not cause the power plant to shut down. It should be noted that the internal network of the wind farm is much more reliable than the wind turbines themselves, so in the case of a wind farm consisting of 10 wind turbines, it is more cost-effective to use the radial structure.

The diagram of the internal grid of the wind farm is presented in Figure 2.

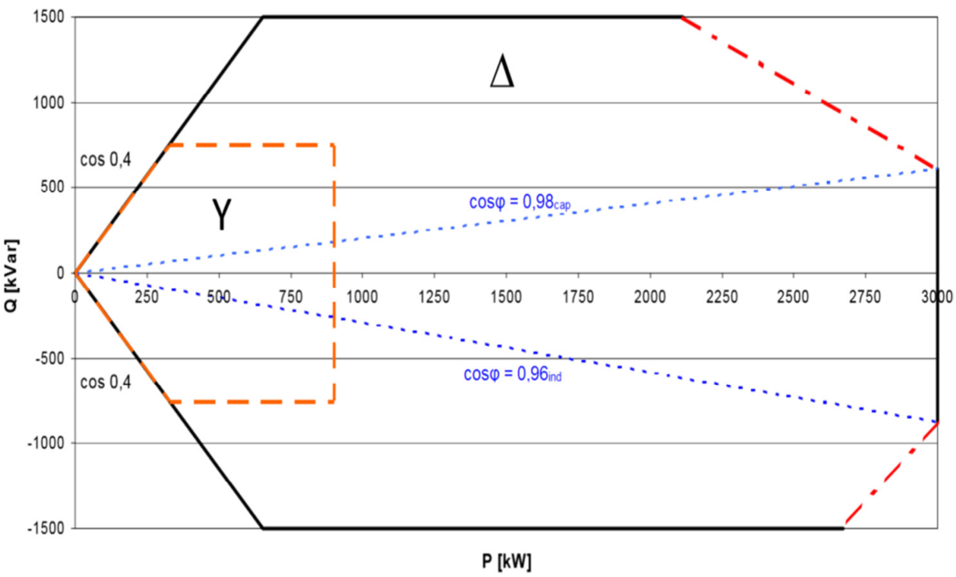

Fig. 1. Characteristic of the Vestas V90 – 3 MW wind turine [12]

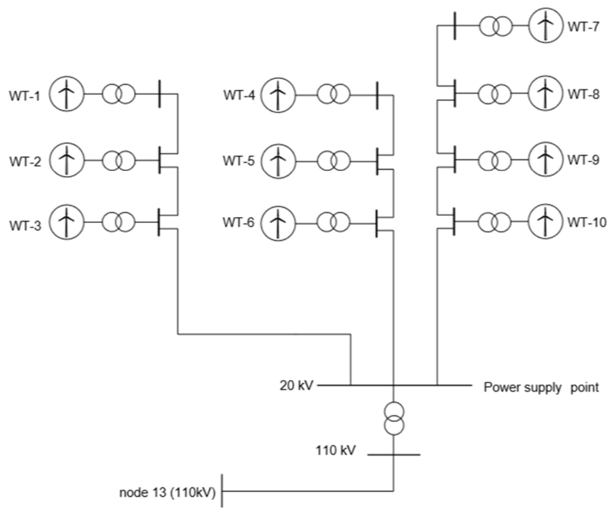

Fig. 2. Wind farm internal network

Figure 3 shows a 110 kV power system model made in Powerworld Simulator software. Wind farm was connected to node 13.

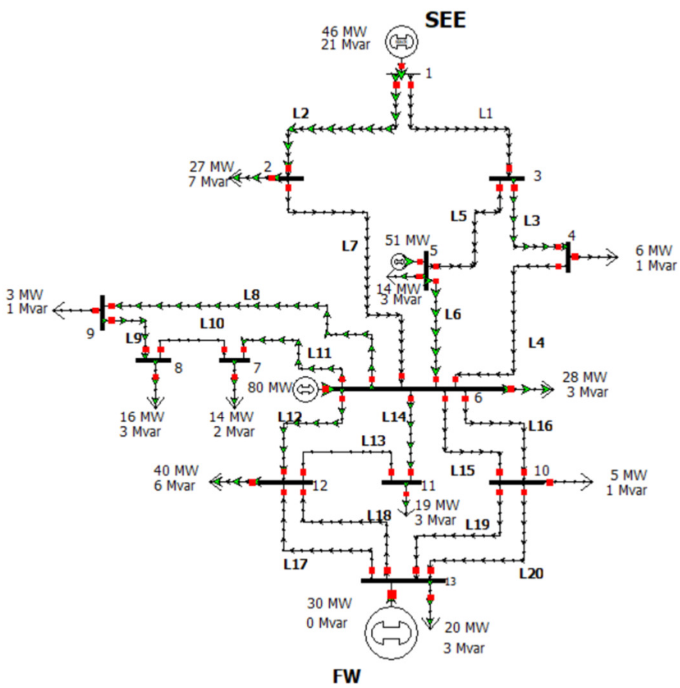

Fig. 3. Power system to which the wind farm is connected

Table 1 shows the transmission lines lengths and used cables and table 2 shows the exact values of active and reactive power received at the nodes.

Table 1. Line lengths and used cables

Line	Conductor	Lenght [km]	Line	Conductor	Lenght [km]
L1	240 AlFe	6.980	L11	240 AlFe	24.452
L2	240 AlFe	8.200	L12	185 AlFe	33.223
L3	185 AlFe	6.000	L13	185 AlFe	24.775
L4	185 AlFe	33.297	L14	185 AlFe	29.333
L5	185 AlFe	13.031	L15	450 AlFe	53.793
L6	185 AlFe	22.329	L16	450 AlFe	53.834
L7	150 AlFe	28.158	L17	185 AlFe	29.164
L8	240 AlFe	22.272	L18	185 AlFe	29.168
L9	240 AlFe	9.096	L19	240 AlFe	9.674
L10	240 AlFe	50.050	L20	240 AlFe	9.681

Table 2. Received active and reactive power

Node number	P [MW]	Q [MVar]	Node number	P [MW]	Q [MW]
1	-	-	8	15.7	3.4
2	27	6.8	9	3.0	1.0
3	-	-	10	4.5	1.1
4	5.6	1.4	11	19.0	3.4
5	14.5	3.4	12	35.8	5.6
6	28.0	3.4	13	15.7	2.2
7	14.5	2.2	-	-	-

The simulations were carried out for different values of active and reactive power generated by the wind farm. The output values of active and reactive power at the connection point of the wind farm were calculated on the basis of simulation of the wind farm's internal network. Internal network model was also made in Powerworld Simulator. Simulations of the internal network were carried out for all anylazed cases in order to determine the output parameters of wind warm taking into account the active power losses in the wind farm network. Active and reactive power generated by individual wind power plants was determined on the basis of the characteristics of Vestas V90. Simulations were made for power factors for which the wind farm works with maximum production of active power - $cos\varphi = 0.98_{cap}$, $cos\varphi = 0.96_{ind}$ and for power factors for which the farm works with undervalued active power which enables higher generation of reactive power.

Figure 4 shows the losses of active power in 110 kV lines in the case of wind turbines operating at a wind speed of 5 m/s. The output power of the entire wind farm is about 1.76 MW.

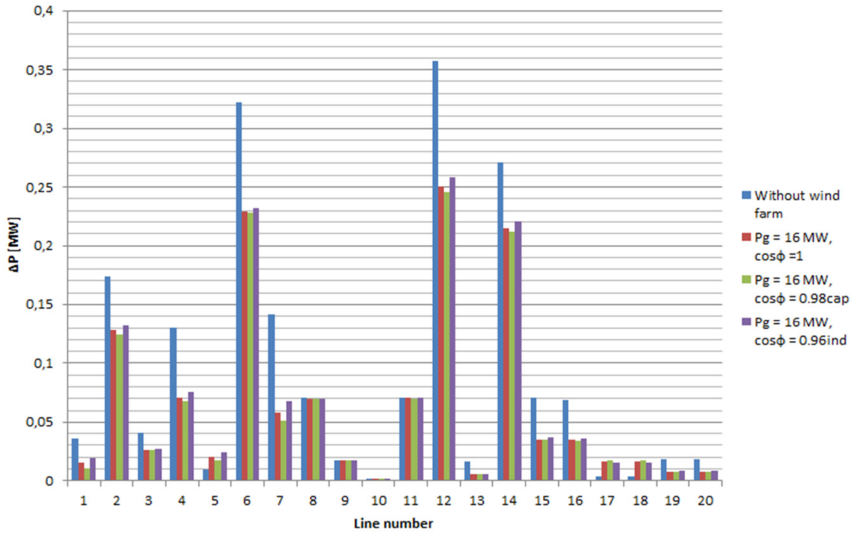

Fig. 4. Active power losses at wind speed of 5 m/s

It can be seen that active power losses in the power system after connection of the wind farm are reduced in comparison to the losses before connection. At low value of generated active power P_g the losses of active power in transmission lines are similar for the analyzed values of power factor *cosφ*.

Figure 5 shows losses of active power in the grid after connecting a wind farm with the generated power at the wind speed of 10 m/s. The output active power generated by entire wind farm is about 16 MW.

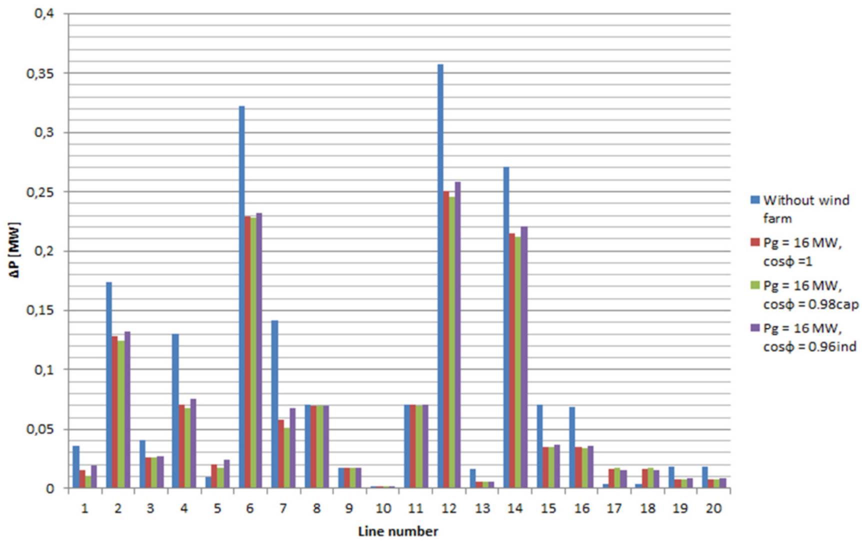

Fig. 5. Active power losses at wind speed of 10 m/s

Active power losses in lines L17 and L18 increases due to the higher current flow in the transmission lines, which is caused by a higher generation of active power, but the overall power losses in the network decreases significantly. When a wind farm consume reactive power from power system, the active power losses are higher than for a wind farm that delivers reactive power to the grid. Losses of active power in the case of a wind farm operating with power factor $cos\varphi = 0.98_{cap}$ are smaller in comparison to the operation with the power factor $cos\varphi = 1$ and for $cos\varphi = 0.96_{ind}$ higher.

Figure 6 shows the active power losses for a wind farm operating with rated power.

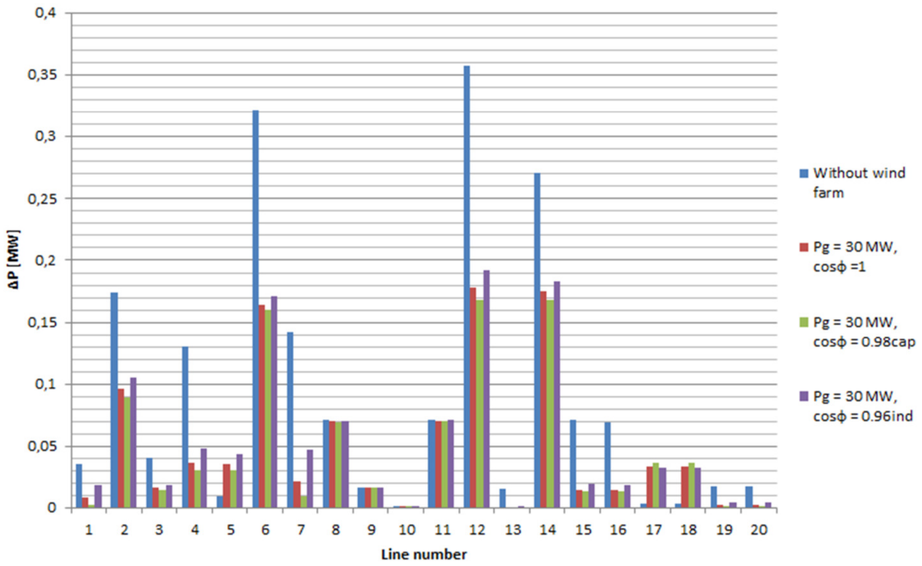

Fig. 6. Active power losses with rated power

Power losses in lines L17 and L18 increase, but total power losses decreased significantly, while in L6 and L12 lines active power losses are 50% lower in relation to grid operation without a wind farm.

Figure 7 shows the losses in case of a wind farm operating with $cos\varphi_{cap}$ and undervalued active power with maximum reactive power generation. The simulations were carried out for wind turbines operating with power:

- P_g = 0.8 MW, Q_g = 750 kVar;
- P_g = 2.0 MW, Q_g = 1500 kVar.

Due to operation with undervalued active power it is possible to achieve a higher voltage at the connection point and in nearby nodes. This allows the wind farms to be used for voltage regulation process.

Higher losses of active power in comparison to a wind farm operating with a power factor $cos\varphi = 0.98_{cap}$ are associated with a much smaller generation of active power.

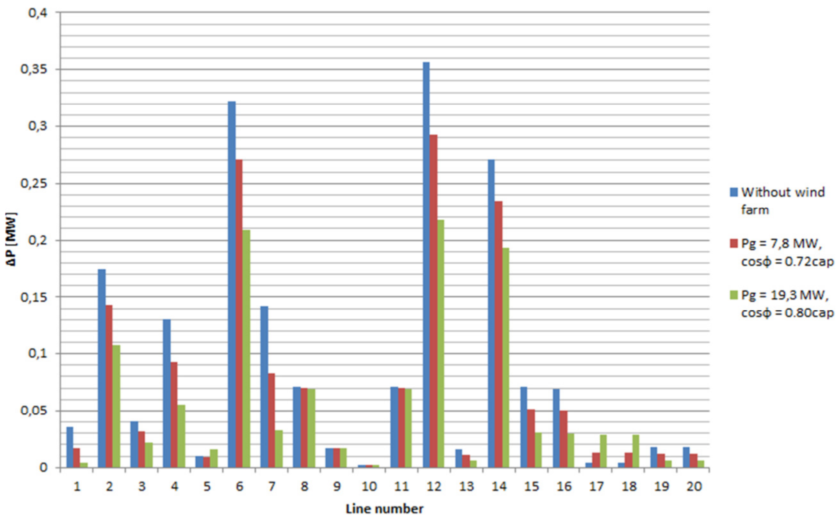

Fig. 7. Active power losses with undervalued active power and $cos\varphi_{cap}$

Figure 8 shows active power losses when the farm is working with $cos\varphi_{ind}$ with undervalued active power. Simulations were carried out for wind turbines operating with:

- $P_g = 0.8$ MW, $Q_c = 750$ kVar;
- $P_g = 2.5$ MW, $Q_c = 1500$ kVar.

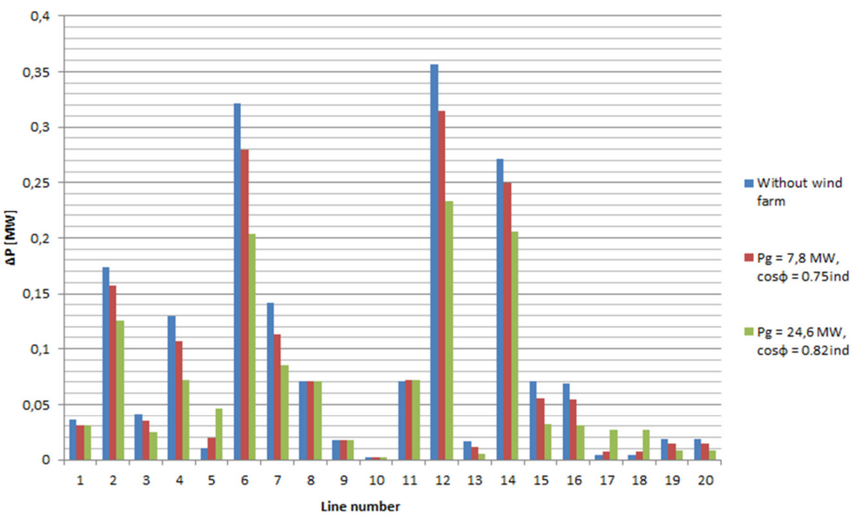

Fig. 8. Active power losses with undervalued active power and $cos\varphi_{ind}$

In that case wind farm consume reactive power from the grid. Consumption of reactive power from the grid may reduce the voltage at the connection point.

It is also possible to maintain a constant voltage when the generated active power increases. As the wind farm becomes another reactive power receiver in the power system, the reactive power line load increases and consequently the active power losses in the grid increases in relation to $cos\varphi_{poj}$.

Figure 9 shows the total active power losses in all transmission lines in the analyzed part of the power system.

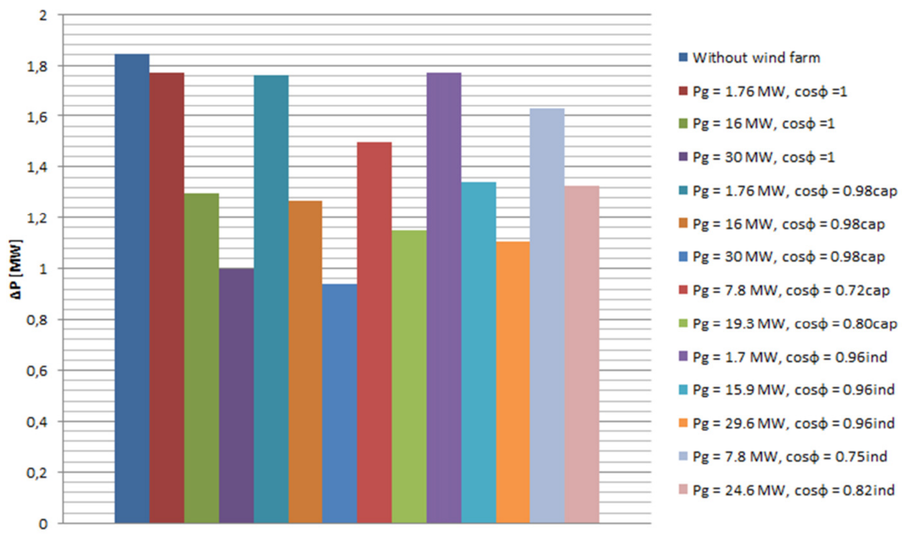

Fig. 9. Total active power losses in analysed grid

On the basis of the above graph it appears that the smallest active power losses in analyzed network occur during the operation of a wind farm with rated active power generation and power factor $cos\varphi = 0.98_{cap}$.

4. Conclusion

Decentralized energy production offers greater opportunities for efficient energy distribution. A larger share of distributed energy sources using renewable energy sources makes it possible to reduce dependence on fossil fuels and increases the security of the power system based on large system power plants.

By connecting generation sources nearby consumers, active power losses in transmission lines can be significantly reduced. The generation of reactive power nearby receiving nodes reduces the load on other lines and reducing the loss of active power.

Connection of wind farms equipped with double-fed induction generators in apart from reducing active power losses in the grid also enables voltage regulation at the connection point and in nearby nodes.

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