

# Analysis of the Selection of Compensation Devices Determining the Reactive Power Balance of Wind Farms

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## ABSTRACT

The construction and installation of high-power wind farms triggers a number of problems related to the compensation of HV cable lines exporting power from a wind farm, and to the choice of compensation devices. The article describes problems that occur when wind farms are connected to the power system with a 110 kV line, characterizes the devices determining the reactive power balance. Two reactive power compensation systems FSR and STATCOM were also analyzed for minimizing the costs of compensation systems.

**Keywords:** reactive power compensation, wind farms, cable lines

## INTRODUCTION

In Poland there is a great interest in the construction of new renewable energy facilities. This interest is a result of the fact that the energy market is shaped by the European Union's policy aimed at reducing carbon dioxide emissions. Among various electrical power generation technologies, which are characterized by a reduction of the adverse impact on the natural environment, the greatest interest is aroused by the objects using solar and wind energy. The value of the wind farms constructed in Poland exceeded 6 GW and it is still growing. According to the assumptions of the Polish Energy Policy (PEP2040), from 2030, the capacity of the onshore farms will be 8 GW, and in 2040, at sea – 10 GW. Wind farms are grouped into installations containing from a dozen to several dozen wind power plants. Such installations, called wind farms, are most often connected to the existing power lines of the 110 kV distribution network. The legal provisions of the Network Transmission Code [1] impose on wind farm investors a need to ensure the regulation of reactive power generated by a wind farm. As a rule, the operator requires that regardless of the level of the active power generated, a farm

should provide, at the coupling point, reactive power resulting from the set power factor (usually it is  $\cos\varphi=0,95$ ). Modern converter systems create a possibility to generate or consume reactive power of  $0,6P_{maxw}$  practically in the entire range of the wind turbine active power generation from 0 to  $P_{maxw}$ . They provide the WindFree function that make it possible for the generators to generate reactive power even in the absence of wind. In spite of this fact, in the conditions of active power generation that is close to the maximum, the introduction of reactive power of  $Q_{PCC} = n \cdot P_{maxw} \cdot tg\varphi_{max}$  to the network by  $n$  wind turbines constituting a farm, encounters numerous difficulties.

## Wind farms and problems of reactive power generation and consumption

The requirements that wind farms have to meet in terms of participation in voltage regulation through the generation or consumption of reactive power consist in the fact that for voltages (at the farm coupling point referred to as PCC – *Point of Common Coupling*) ranging from 105kV to 120 kV, a farm can show a zero reactive power flow [2], [9]. For low voltage values (below 100 kV), a farm should generate maximum

reactive power, and with voltage above 125 kV, it should take maximum reactive power.

Among various problems associated with the construction of wind farms and their integration with the power system, there is one essential aspect of these farms' participation in the global use of reactive power of the power system and its significance for maintaining proper voltage levels and achieving permanent voltage stability. While considering the production and consumption of reactive power by a wind farm, it should be remembered that the following devices and installation are involved in this process: power plant generators, medium voltage cables, power capacitor banks connected on the MV side, HV/MV transformer, HV cable connecting the farm switching station with the farm coupling point to the network (PCC), a choke connected to the HV network and a supplementary control choke connected on the MV side of the farm. The efficiency and possibility to generate (or consume) power by a wind farm are not based only on their owners' policy. They are imposed on network operators who, in turn, are forced to apply specific policy towards investors and farm owners by specific technical standards of the European Union, responsibility for the security of the power system and a commercial view on the costs of distribution of the energy produced by the wind farms. According to the currently applicable regulations, excessive reactive power consumption is subject to financial penalties imposed by distribution network operators. Financial penalties for extra-contractual consumption or production of reactive energy are imposed on all consumers (producers) using medium or high voltage networks.

## Devices determining reactive power balance

### Capacitor banks

Capacitor banks are considered as a backup reactive power source for wind farms installed on the medium voltage side of the 110/MV main switchgear. It seems that due to a possibility of reactive power generation by power electronics systems of wind generators, an additional reactive power generation is unnecessary. It turns out, however, that with full active power generation, the reactive power production capacity of generators is reduced and the reactive power losses on longitudinal cables and transformer reactance increase. Therefore, it may turn out that capacitor banks are necessary. Typical unit powers are 0,5 Mvar, 1 Mvar, 2 Mvar. The power of these devices is not adjustable, that is why the necessary values of reactive power are obtained by switching on the appropriate number of capacitor banks. It should be remembered that a given rated power is obtained under rated voltage conditions on the capacitor bank clamps.

In another case, there is a dependence:

$$Q_c = Q_{cn} \cdot \left( \frac{U}{U_n} \right)^2 \quad (1)$$

In computational analyses, capacitor banks are mapped using  $B_C$  susceptance determined from the formula:

$$B_C = \frac{Q_{cn}}{U_n^2} \quad (2)$$

From the point of view of optimization of the wind farm reactive power compensation system, the prices of capacitor banks connected on the MV side are also essential.

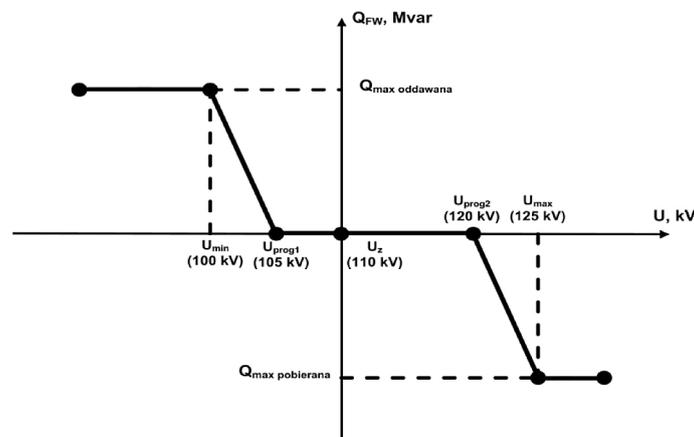


Fig. 1. Characteristics (U,Q) required for reactive power of farms connected to the 110 kV according to [2]

### Static VAR compensator SVC and STATCOM systems

The name static compensators SVC refers to the systems consisting of passive elements (chokes, capacitors) connected or regulated by means of thyristors. An adjustable choke operates at low compensator power and when the power increases, a second choke is activated. TSC (Thyristor Switched Capacitors) is a system in which the capacitor banks are connected to the power supply system with a thyristor switch.

The TCR/FC system (Thyristor Controlled Reactor, Fixed Capacitor) consists of a permanently connected capacitor and an adjustable choke. The last type of TSC/TCR compensator consists of an adjustable reactor and a capacitor bank connected with the thyristor [4, 6].

The devices called STATCOM are more modern and technically advanced systems. They consist of an electronic power converter connected to the network and loaded with a capacitor bank. Owing to the converter's properties and appropriate control algorithm, reactive power can be "injected" into the network, but it can be also taken from the network. The regulation is smooth within a wide range, a "disadvantage" of the STATCOM systems is their high price [5, 6].

### Shunt reactor

The shunt reactor is the basic compensation device. The 110 kV shunt reactor of several dozen megavars (Mvar) are expensive devices. Their price varies significantly depending whether the inductance of a choke is regulated and on the accuracy of this regulation. The choke is at the same time a source of energy loss which increases the annual costs of its operation. The process of a

proper selection of the compensation device is further complicated by the fact that neither the 110 kV cable capacity nor the inductor inductance are parameters whose value is strictly determined. Cables are produced in short series, practically for a specific investor's order. Similarly, chokes are manufactured as unitary devices. Therefore, their basic rated parameters (cables –  $C_n$ , shunt reactors –  $L_n$ ) are in a sense random variables. As a result, a compensation device made according to the data of the designed cable line will not release an investor from high annual operating costs of the "cable-shunt reactor" system [2, 8].

### EU requirements with respect to generation and consumption of reactive power by wind farms

The European Union Regulation No. 631 of 2016 [3,7] introduced a number of requirements for generating sources connected to the power network (hence the acronym describing this regulation – RfG – *requirements for generation*). Wind farms with the capacity of above 50 MW are classified as sources of C and D type, and apart from that, the legislator classifies them as power park modules (PPM) by setting specific requirements for the coupling point to the SEE, for capacities above 50 MW, it is usually the 110 kV network. Part of these requirements are related to the ability to generate and consume reactive power by PPM (understood as a whole, i.e. 110 kV internal line, 110/MV transformer, MV cable network, wind turbine generators MV/LV systems. The basic source of reactive power for PPM installations (Power Park Module) are installed the generating

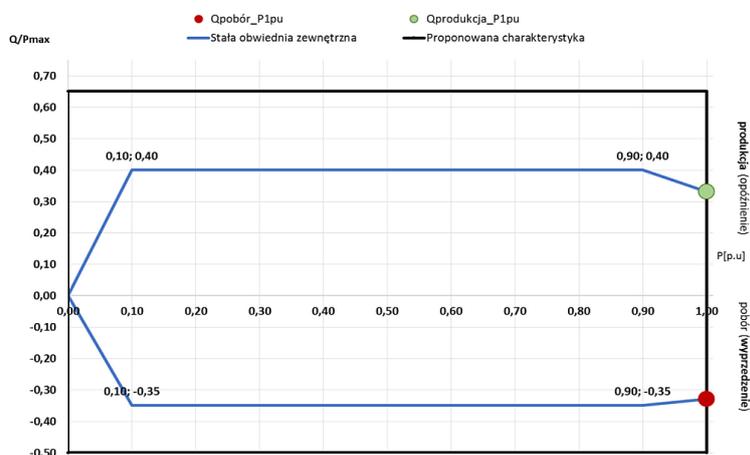


Fig. 2. Characteristics of reactive power generation capabilities of a typical wind farm generator adopted for computational analyses

devices installed in it. For modern wind farm generators, the possibilities of reactive power generation and consumption are very wide. Figure 2 presents the requirements that wind farms set for reactive power EU Regulation 2016/631 – generation and consumption must reach the values marked with a blue line. The maximum reactive power generation in the presented diagram reaches the value of  $0,4P_{gn}$ . The same applies to reactive power consumption, but the reactive power has the opposite sign, whereas the reactive power value is to reach the value of  $0,35 P_g$ .

According to the requirements, the farm production capabilities with respect to reactive power should comply with the graph shown in Fig. 3. During approximately 1500 hours, zero reactive power consumption (generation) is required. During the remaining time of the year, approximately 7200 h farm should be able to generate reactive power of  $Q_{max, req} = 24$  Mvar or reactive power consumption of  $Q_{min, req} = -21$  Mvar. It is necessary that a farm should be ready to meet each of these requirements in each hour of its operation.

According to the characteristics presented in Figure 2, the network operator’s requirements for Power Park Module (PPM), they can be presented with the following dependences:

for  $P_F > 0$  the reactive power required

$$-0,35 P_{nF} \leq Q_{PCC} \leq 0,4 P_{nF} \quad (3a)$$

for  $P_F = 0$  the reactive power required

$$Q_{PCC} = 0 \quad (3b)$$

Due to the fact that a farm with  $P_{nF} = 60$  MW was analysed, according to the requirements described above, its reactive power should range from  $Q_{gmin} = -21$  Mvar to  $Q_{gmax} = 24$  Mvar, provided

that the active power generation is not zero. What is important, is a farm ability to reach the required extreme values, that is  $Q_{gmin}$  and  $Q_{gmax}$ . However, if a farm is not working, then the reactive power at the PCC should be also zero. The latter condition has a significant financial dimension, since according to the provisions [8,9], the non-zero state of reactive power generation (or consumption), with zero active power generation, is subject to an annual fee.

### Analysis of possibilities of meeting wind farm reactive power generation and consumption requirements

#### Fixed Shunt Reactor FSR

The annual course of variability in generation deficits and reactive power consumption is determined, apart from the active power generation level, by the way the compensation choke works. The simplest solution is a fixed, permanent choke so that the 110 kV cable capacity could be compensated, according to the dependence:

$$L_{DS} = \frac{10^9}{\omega_n^2 \cdot l_{kWN} \cdot c_{kWN}} \quad [\text{mH}] \quad (4)$$

where:  $L_{DSN}$  indicates the choke inductance  
 $l_{kWN}$  the analyzed HV farm cable length  
 $c_{kWN}$  unit capacity of the HV farm cable  
 $\omega_n = 314$  1/s network pulsation

Figure 4 presents the size of the deficit depending on the active power generated in the farm. In spite of calculations for different lengths of cable lines, the deficits do not differ significantly, particularly for generated power less than approx. 10 MW with respect to active power ranging from

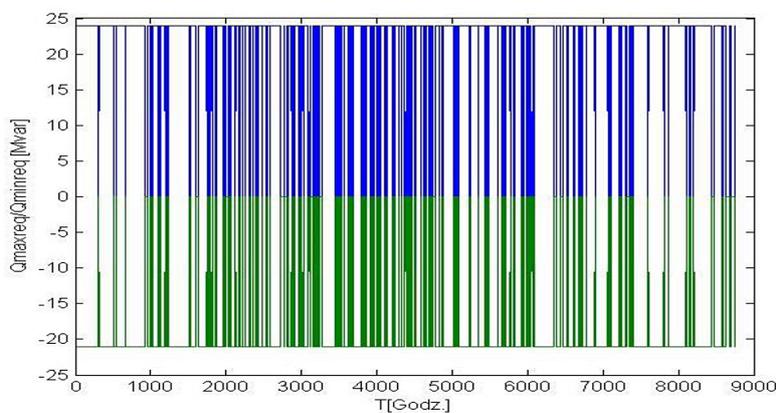


Fig. 3. The requirements for the reactive power generation and consumption capacity of a 60 MW wind farm based on the characteristics (according to the EU Regulation 2016/631)

10 MW to 40 MW, the reactive power deficit in both generation and consumption does not occur.

The overall assessment of compliance with these requirements can be determined by introducing appropriate indicators. The total demand for reactive power generation and consumption during the year is expressed by the following dependences:

$$A_{Q_{\max}} = \sum_{j=1}^{k_j} Q_{\max\_req} T_j \quad (P_{Fj} > 0) \quad (4a)$$

$$A_{Q_{\min}} = \sum_{j=1}^{k_j} Q_{\min\_req} T_j \quad (P_{Fj} > 0) \quad (4b)$$

where:  $\Delta A_{Q_{\max}}$  – total annual deficit of reactive power generation according to the EU requirements 2016/631, it is a function of many variables, especially the degree of choke compensation in relation to the exact compensation,

$\Delta A_{Q_{\min}}$  – total annual deficit of reactive power consumption according to the EU requirements 2016/631, it is a function of many variables, especially the degree of choke compensation in relation to the exact compensation,

$\Delta Q_{\max\_req}(l)$  – reactive power generation deficit in the l-th hour,

$\Delta Q_{\min\_req}(l)$  – reactive power consumption deficit in the l-th hour,

$P_F$  – farm active power,

$T_j$  – time (hours).

The total deficit of reactive power generation abilities and the total deficit of reactive power

consumption abilities are determined by the following dependences:

$$\Delta A_{Q_{\max}} = \sum_{p=1}^{k_p} \Delta Q_{\max\_req(p)} T_p \quad (\Delta Q_{\max(p)} > 0) \quad (4c)$$

$$\Delta A_{Q_{\min}} = \sum_{p=1}^{k_p} \Delta Q_{\min\_req(p)} T_p \quad (\Delta Q_{\min(p)} < 0) \quad (4d)$$

where:  $\Delta A_{Q_{\max}}$  – the annual deficit of readiness for reactive power generation in compliance with the EU requirements 2016/631, it is a function of many variables, especially the degree of choke de-compensation in relation to the exact compensation (variable  $r_D$ );

$\Delta A_{Q_{\min}}$  – the annual deficit of readiness for reactive power compensation in compliance with the EU requirements 2016/631, it is a function of many variables, especially the degree of choke de-compensation in relation to the exact compensation (variable  $r_D$ ); the absolute value was used due to the negative sign of this power;

$\Delta Q_{\max\_req}(l)$  – reactive power generation deficit in the l-th hour;

$\Delta Q_{\min\_req}(l)$  – reactive power consumption deficit in the l-th hour;

whereby the  $p$  index refers to hours of the year with a deficit of the required generation (consumption) of reactive power.

Figure 5 presents the dependence of the value of the multi-criteria quality indicator on the degree of de-compensation of the choke connected on the HV farm side. The zero de-compensation degree means that the choke inductance was



**Fig. 4.** Dependence of the wind farm's generation deficit and reactive power consumption, depending on the active power generation (in compliance with the requirements of the EU Regulation 2016/631); the compensation choke tuned exactly to the capacity of the 110 kV cable line (line lengths of 5, 15, 25, 50 km)

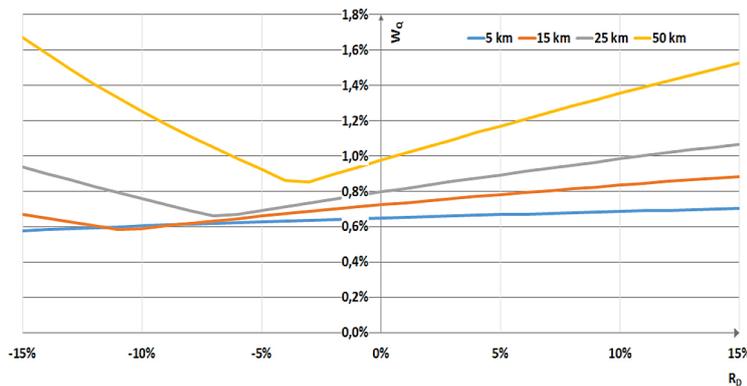
chosen exactly according to the (4.1) dependence. As the calculations show, the longer the 110 kV cable line, the more clearly the minimum value of the  $W_Q$  quality indicator is seen, for a certain degree of de-compensation. For lines of 50 km, the best quality of the compensation system occurs with the de-compensation of approx. -4%. In such a case, the choke takes all excess reactive power coming from the MV cables and the penalty fees for reactive power flow when the farm does not work are reduced almost to zero. The shorter the cable line, the less clear the existence of the extreme for the function  $W_Q = f(r_D)$  becomes. The required de-compensation for a very short 110 kV cable line is even -15%, because only for such a value the flow of capacitive power is reduced when a farm does not work.

Figure 6 shows annual changes in reactive power deficit for the 110 kV cable line of 50 km

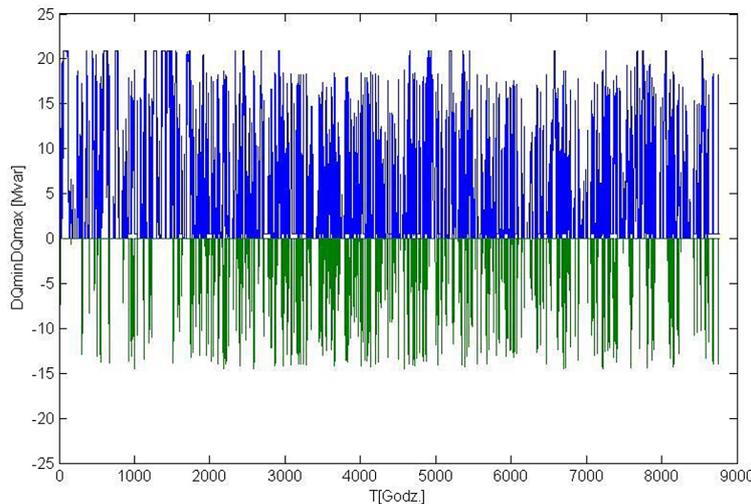
in case of de-compensation  $r_D = -5\%$ . The reactive power generation ability decreases slightly, but the excess reactive power while working with zero active power is more effectively compensated (the penalty fee is smaller).

### STATCOM converter compensator

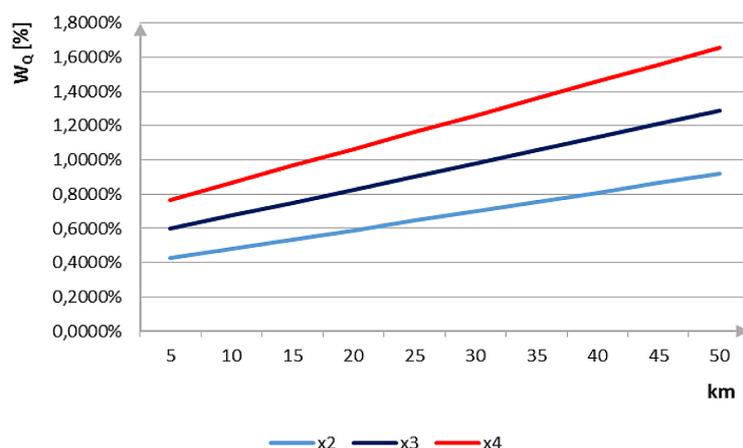
A converter device called STATCOM was considered as the most technologically advanced compensation system. Due to a possibility of smooth regulation of reactive power (both in terms of generation and consumption), as well as a possibility to eliminate reactive power flow through PCC when a farm does not work, this device ensures a zero value of the first two components of the  $W_Q$  compensation quality indicator. There is no penalty fee for the reactive power deficit in meeting the requirements of the EU



**Fig. 5.** The quality indicator  $W_Q$  of reactive power compensation for a non-adjustable choke, determined for different degrees of  $r_D$  de-compensation related to the choke inductance, corresponding to the HV cable capacity; calculations made for the HV cables of 5, 15, 25 and 50 km



**Fig. 6.** The course of annual changes in the deficit of readiness for generation and consumption of reactive power (in compliance with the EU requirements 2016/631) by a 60 MW wind farm; de-compensated compensation choke for  $r_D = -5\%$ , in relation to the 110 kV cable line capacity (line length of 50 km)



**Fig. 7.** The values of the  $W_Q$  quality indicator of a wind farm reactive power compensation for the STATCOM device and adjustments that meet all the requirements of the EU 2016/631 network operators; calculations made for the HV cables of 5, 15, 25 and 50 km for various multipliers of compensator costs related to the FSR

Regulation 2016/631, or a penalty for non-zero reactive power flow when a farm does not work. Due to the fact that the maximum value of reactive power consumed should cover the demand for compensation of the capacitive power of the 110 kV cable and MV cables, and the reactive power consumption required by EU 2016/631, for a 50 km line and the farm in question of the 60 MW farm, the power of the STATCOM device should be approx. 53 Mvar. As a result, the quality indicator is almost twice as high as the value of the  $W_Q$  indicator for a choke without FSR regulation. Thus, it can be concluded that technology loses to economics. The decrease of a cost multiplier to the value of 2 indicates the attractiveness of using the STATCOM device for the 110 kV line of short length. These dependences are shown in Figure 7.

## CONCLUSION

Considering two FSR and STATCOM reactive power compensation systems on the grounds of the quality indicator, they were compared in terms of minimizing the costs of compensation systems. Various lengths of 50km and 5 km cable lines were analyzed. The best solution for the cable length of 50 km is a choke with a set inductance value (FSR) slightly de-compensated in relation to the cable capacity ( $r_D = -3,1\%$ ), worse results of the  $W_Q$  compensation quality indicator were obtained in case of the STATCOM device, which exactly meets the requirements of the EU 2016/631 document, but its price is too high. A better solution for a short 5 km cable line is using the STATCOM device whereas the FSR choke has worse parameters.

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