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Generation and absorption of reactive power by wind farms – consequences of implementation of EU regulation 2016/631

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Abstract: The article presents the consequences of the introduction of EU regulation 2016/631 for power park modules (PPMs), of which wind farms are a typical example. Analysing the yearlong course of changes in the generated power, the possibility of a typical wind farm meeting the requirements for the production and absorption of reactive power was checked. It was shown that in the selected cases it was necessary to introduce additional sources of reactive power on the side of the farm's MV.

Key words: reactive power, wind farms

1. The essence of the requirements of EU regulation 2016/631 regarding generation of reactive power

European Union Regulation No. 631 of 2016 – [3] introduced a number of requirements for generation sources connected to the power grid (hence the acronym describing this regulation – RfG – *requirements for generation*). Wind farms with a capacity above 50 MW are classified as C and D type sources, and the legislator classifies them as power park modules (PPM) with specific requirements for the power system connection point (for capacities above 50 W it is usually a network with 110 kV). Some of these requirements regarding the generation and reactive power capability of PPMs (understood as a whole, i.e. a 110 kV internal line, 110 MV transformer, MV cable network, wind turbine generators with MV/LV converter systems) are cited below:

Art. 21 pt. 3c

(i) the relevant system operator in coordination with the relevant TSO (Transmission System Operator) shall specify the reactive power provision capability requirements and shall specify a

$P-Q/P_{\max}$-profile that may take any shape within the boundaries of which the power park module shall be capable of providing reactive power below maximum capacity;

(ii) the $P-Q/P_{\max}$-profile shall be specified by each relevant system operator in coordination with the relevant TSO, in conformity with the following principles:

- the $P-Q/P_{\max}$-profile shall not exceed the $P-Q/P_{\max}$-profile envelope, represented by the inner envelope in Figure 9,
- the $Q/P_{\max}$ range of the $P-Q/P_{\max}$-profile envelope is specified for each synchronous area in Table 9,
- the active power range of the $P-Q/P_{\max}$-profile envelope at zero reactive power shall be 1 pu,
- the $P-Q/P_{\max}$-profile can be of any shape and shall include conditions for reactive power capability at zero active power, and
- the position of the $P-Q/P_{\max}$-profile envelope shall be within the limits of the fixed outer envelope set out in Figure 1.

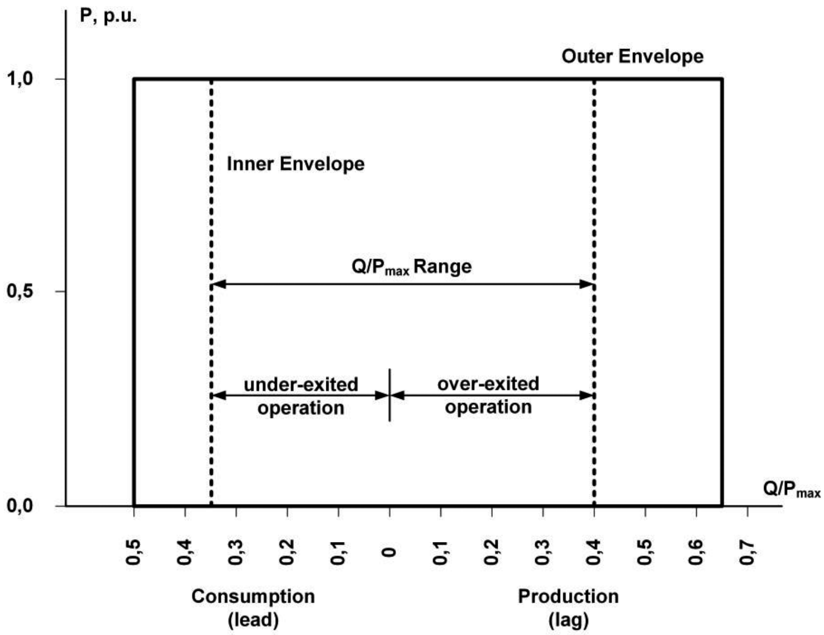

Fig. 1. Defining the scope of requirements regarding the reactive power capability for power park modules (PPMs) according to the requirements of EU regulation 2016/631

This means that the network operator can choose the characteristics shown in Figure 2, and the wind farm owner (i.e. power park modules, or PPM, in general) has to meet this requirement at any moment of the farm operation ("moment" is understood as a quarter of an hour, and reactive and active power values are averaged) for this period of time.

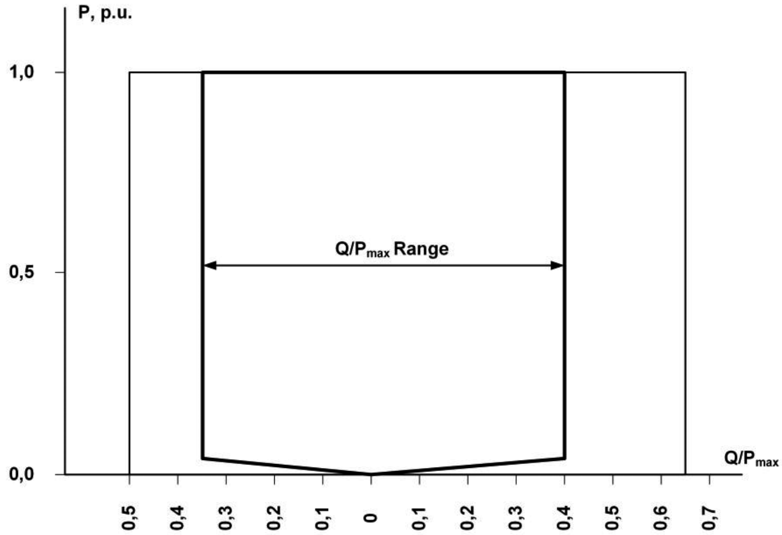

Fig. 2. Reactive power characteristics at the PPM (Power Park Module) connection point determined in accordance with the requirements of EU regulation 2016/631 by the network operator for the wind farm in question

2. Generation and absorption of reactive power by a wind farm

The basic source of reactive power for PPM installations are the production devices installed in it [5–10]. For modern wind turbine generators the possibilities of generating and absorption reactive power are very wide. The shape of a typical characteristic of the available reactive power as a function of the active power generated is shown in Figure 3. The arrows indicate the

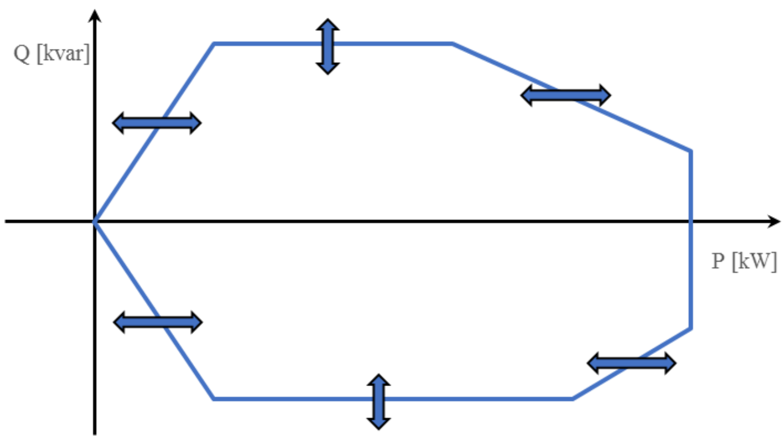

Fig. 3. Characteristics of the reactive power capability of a typical wind farm generator (arrows indicate possible changes in the value of the characteristics parameters)

possibility of determining the final shape of this characteristics. In the analyses performed, the characteristics of the parameters shown in Figure 4 were used. It is similar to the characteristics of the Vestas generator [1, 2]. As can be seen, both reactive power generation and consumption reach $0.5P_{gn}$, but for power smaller than $0.2P_n$ and closer to P_n the generation possibilities are limited. The same remark concerns the absorption of reactive power, only reactive power has the opposite sign.

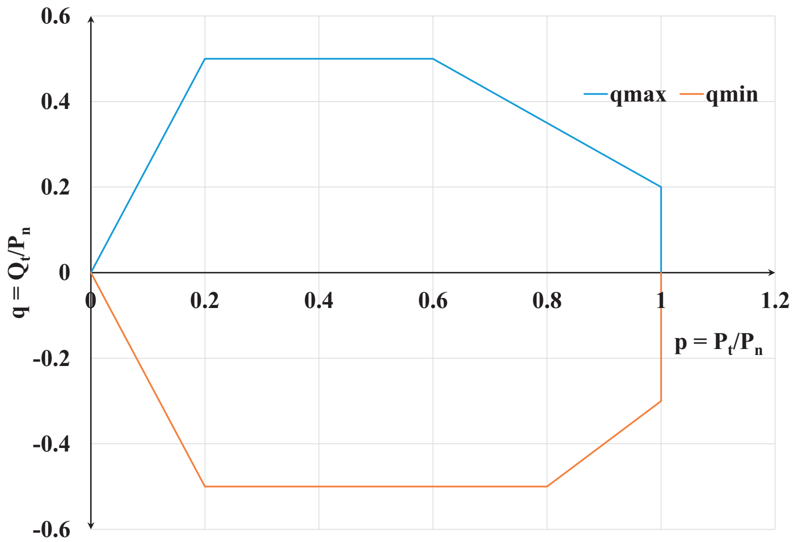

Fig. 4. Characteristics of the reactive power capability of a typical wind power plant generator adopted for computational analyses

Considering the simplified scheme of the internal network of the wind farm (Figure 5), the following reactive power sources and relays can be distinguished in it, which as a result determine the reactive power balance at the connection point (PCC) and whether the requirements set in EU 2016/631 can be met:

– generation or absorption – wind farm generators (generation or reactive power absorption is possible in accordance with the characteristics shown in Figure 4);
– generation – MV cable lines, generally 30 kV (regardless of the wind generation status, they generate reactive power due to the capacity of the cables);
– absorption – 30 kV cable lines (depending on the value of power generated by windmills there are longitudinal losses of reactive power due to the inductance of cables);
– absorption – a 110/30 kV transformer (depending on the total apparent power from the 30kV line, there are reactive power losses on the longitudinal reactance and voltage losses towards magnetizing the core);
– generation – a 110 kV cable from the farm to the system, due to the capacity, is a very significant source of reactive power if the line is several dozen or several dozen kilometers; in general, this power should be compensated by means of a reactor, but it can also be used as a source of passive power;

– absorption – a 110 kV compensating reactor is a reactive power absorption, compensating for the reactive power of the cable line, but working in conditions of overcompensation or undercompensation it may affect the reactive power balance in the PCC (if its parameters allow it);
– absorption – a 110 kV cable, in which, depending on the square of apparent power transmitted, there are reactive power losses due to its inductance;
– generation – a capacitor bank installed on the 30 kV side in the event of a shortage of reactive power can help meet the balance requirements (if the generation coming from a 110 kV cable turns out to be insufficient).

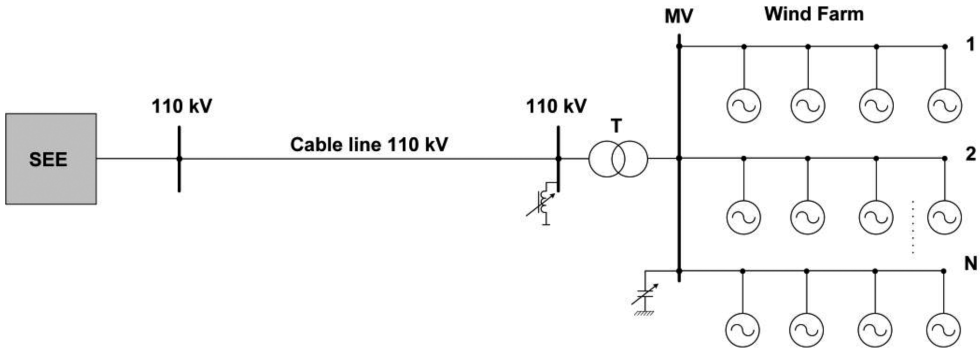

Fig. 5. Diagram of the 110/30 kV internal wind farm network (reactive power requirements refer to the connection point to the 110 kV grid)

The network visible in Figure 5 can be assigned as an exact model (in the sense of load flow calculations) visible in Figure 6. Such a model can be the subject of analysis conducted with the use of specialized load flow software. However, it is possible to use a simplified model, for which the balance relationships for reactive power at the PCC can be expressed using simple formulas.

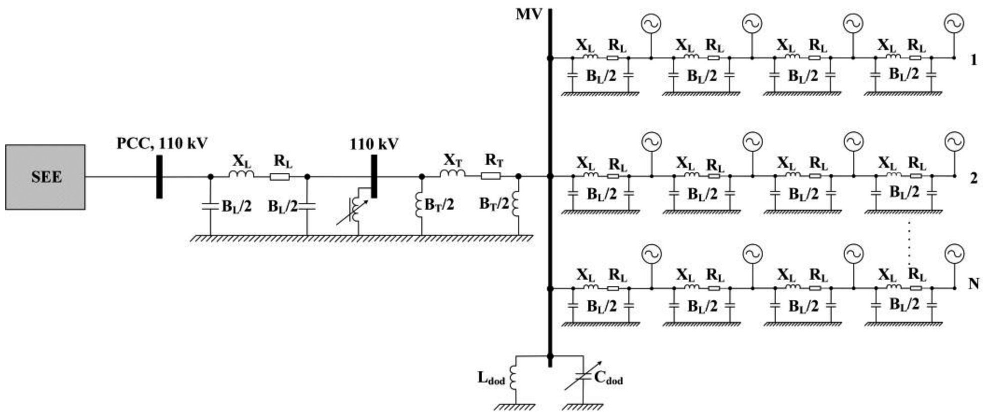

Fig. 6. Scheme of the R, X, B calculation model of the 110/30 kV wind farm's internal network (reactive power requirements refer to the connection point to the 110 kV grid)

According to the shape of the characteristic curve shown in Figure 2, the network operator's requirements for a PPM can be saved by means of the following relationships:

$$\text{for } P_F > 0 \text{ reactive power required } -0.35P_{nF} \leq Q_{PCC} \leq 0.4P_{nF}, \tag{1a}$$

$$\text{for } P_F = 0 \text{ reactive power required } Q_{PCC} = 0. \tag{1b}$$

Considering the fact that a farm with a capacity of $P_{nF} = 60$ MW was analyzed, in accordance with the requirements specified above, its reactive power should be in the range from $Q_{g\,\text{min}} = -21$ Mvar to $Q_{g\,\text{max}} = 24$ Mvar, unless the active power generation is zero. If the farm stands idle (due to the lack of wind) then the reactive power at the PCC should also be zero. The last condition has a significant financial dimension, because according to the provisions [4], a non-zero state of generation (or absorption) of reactive power with zero active power generation is subject to an annual fee

$$K_Q = \sum_{j=1}^{k_i} k_k \cdot e \cdot \Delta Q_j \cdot T_j\,, \tag{2}$$

wherein:
- k_k is the coefficient (for a 110 kV network it is 0.5),
- e is the price of electricity according to the annual URE valuation (PLN 200/MWh),
- ΔQ_j is the imbalance to zero of reactive power in the j-th period of idle farm work,
- T_j is the duration of the farm's idle period.

3. Analysis of the possibilities to meet the generation and absorption requirements of reactive power

Annual variation of wind speed (in the case at hand the maximum value is 18.6 m/s, at an average during the year of 6.75 m/s) results in changes of the active power generated by the farm – from the maximum value – 60 MW to zero. The idle period, that is one for which the wind speed is less than 4 m/s, is about 1500 hours. The graph corresponding to the variation of active power generation during the year is shown in Figure 7. According to the requirements formulated above, the farm's production capacity in the reactive power range should be shaped according to the diagram shown in Figure 8.

Balancing the generation capacities of generators of individual windmills, the generation of reactive power in MV cables and a 110 kV cable, as well as taking into account the longitudinal losses changing with the square of the active power generation, it is possible to determine the maximum and minimum reactive power values available at PCC for the considered j-th moment, with zero active power generation. It turns out that for certain conditions, the requirements for generation and reactive power consumption determined in accordance with the characteristics of Figure 2 cannot be met, because

$$Q_{\text{max\_PCC}j} < Q_{\text{max\_req}}, \tag{3a}$$

$$Q_{\text{min\_PCC}j} > Q_{\text{min\_req}} \tag{3b}$$

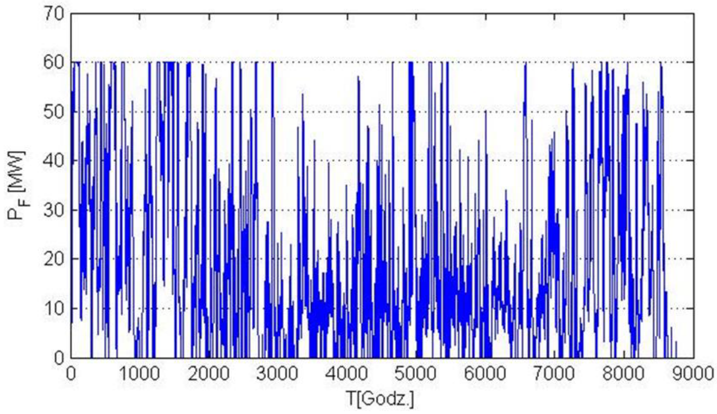

Fig. 7. Graph of the annual course of active power achievable by the considered wind farm with 60 MW (wind conditions for a hypothetical facility located in the northern part of Mazovia, Poland)

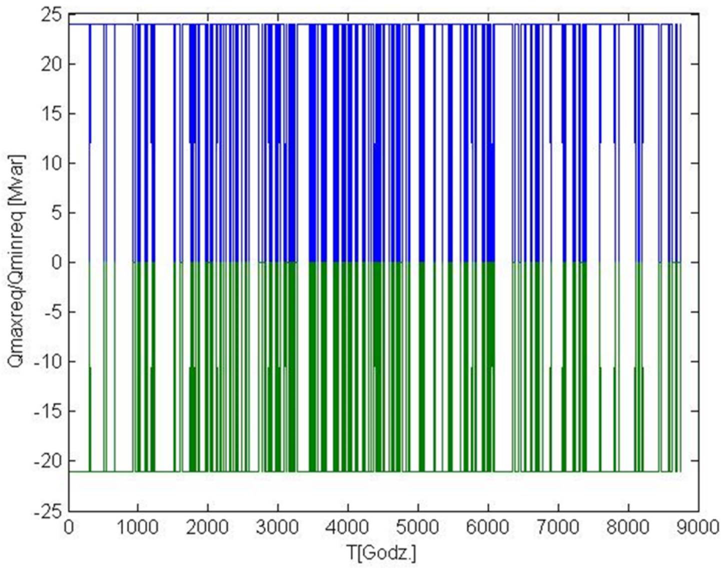

Fig. 8. Requirements for generation and reactive power consumption by a 60 MW wind farm determined on the basis of the characteristics from Figure 2 (in accordance with EU Regulation 2016/631)

and additionally

$$Q_{\mathrm{PCC}j} \neq 0 \quad \text{for} \quad P_F = 0, \tag{3c}$$

wherein

$$Q_{\max\_\mathrm{req}} = 0.4 P_{nF} = 24 \text{ Mvar}, \tag{4a}$$

$$Q_{\min\_\mathrm{req}} = -0.35 P_{nF} = -21 \text{ Mvar}. \tag{4b}$$

The annual passages of the generation/absorption of reactive power are shown in Figures 9, 10 and 11 for considered farm 60 MW. Their shape and course depends on the way the reactor compensates for the reactive power of the 110 kV cable (length 50 km) – whether it is fixed, satisfying the condition of effective compensation (Fixed Shunt Reactor) or has the ability to change parameters in order to meet the requirement (1a), while meeting the requirement (1b) under the conditions of zero power generation by the farm.

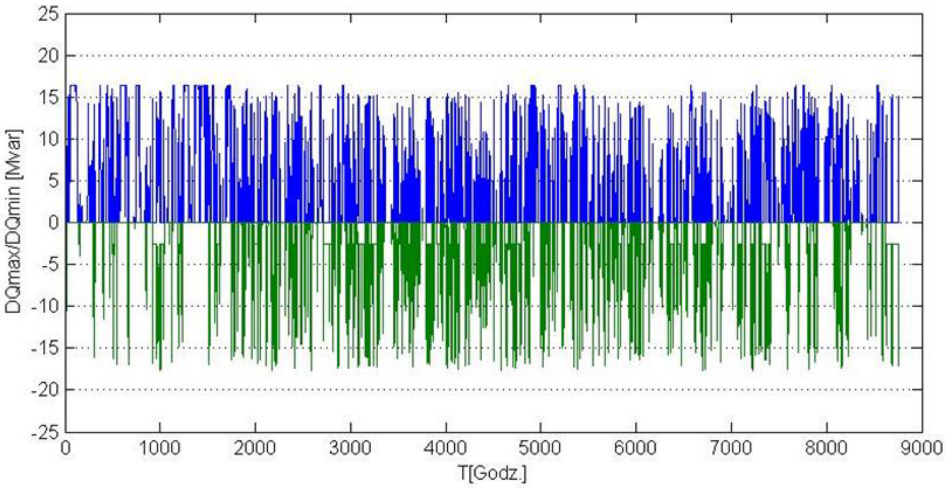

Fig. 9. The course of annual changes in the deficit in readiness for generation and reactive power absorption (according to the requirements of EU regulation 2016/631) by a 60 MW wind farm; compensating reactor tuned exactly to the capacity of the 110 kV cable line

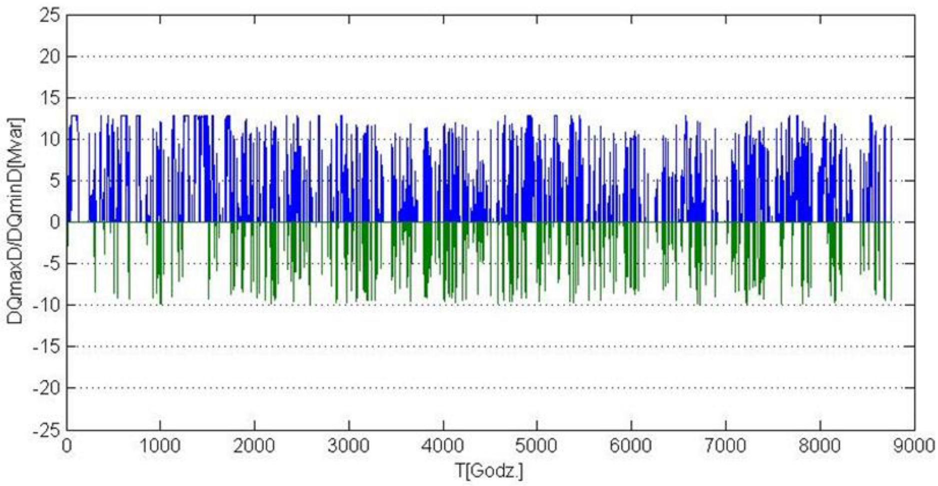

Fig. 10. The course of annual changes in the deficit in readiness for generation and reactive power absorption (according to the requirements of EU regulation 2016/631) by a 60 MW wind farm; compensating reactor with continuous regulation in the range from 1800 to 3800 mH

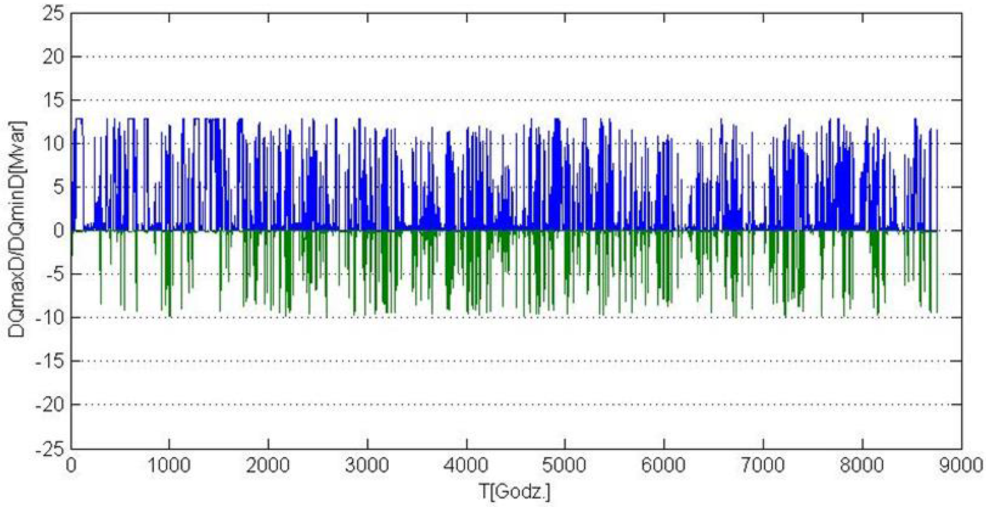

Fig. 11. The course of annual changes in the deficit in readiness for generation and reactive power absorption (as required by EU regulation 2016/631) by a 60 MW wind farm; compensating reactor with step adjustment in the range from 1800 to 3800 mH, 11 taps every 200 mH

The aggregate assessment of the fulfilment of these requirements can be determined by introducing appropriate indicators, in accordance with dependencies:

$$A_{Q\,\max} = \sum_{j=1}^{k_j} Q_{\max\_\mathrm{reg}} T_j \quad (P_{Fj} > 0), \tag{5a}$$

$$A_{Q\,\min} = \sum_{j=1}^{k_j} Q_{\min\_\mathrm{reg}} T_j \quad (P_F > 0), \tag{5b}$$

$$A_{Q\,\max} = \sum_{p=1}^{k_p} \left(Q_{\max\_\mathrm{reg}} - Q_{\max p} \right) T_p = \sum_{p=1}^{k_p} \Delta Q_{\max p} T_p\,, \tag{5c}$$

$$A_{Q\,\min} = \sum_{l=1}^{k_l} \left(Q_{\min\_\mathrm{reg}} - Q_{\min l} \right) T_l = \sum_{l=1}^{k_l} \Delta Q_{\min l} T_l\,, \tag{5d}$$

whereby the p index applies to periods of the year with a deficit of the required reactive power generation, and the index l to periods with a deficit of the required power absorption.

The reference of the “readiness deficit” to the value of the annual requirements for the generation or absorption of “reactive energy” (the quotes signal the authors’ doubts about the physical meaning of this concept) allows a comprehensive comparison of the effectiveness of individual wind farm electrical systems in terms of meeting the requirements of EU regulation 2016/631.

$$a_{Q\,\max} = \frac{\Delta A_{Q\,\max}}{A_{Q\,\max}} \cdot 100\%\,, \tag{6a}$$

$$a_{Q\,\min} = \frac{\Delta A_{Q\,\min}}{A_{Q\,\min}} \cdot 100\%\,. \tag{6b}$$

Indicators (6a) and (6b) for ideally matched generation/absorption of reactive power capacities of a farm should have a zero value. A non-zero value indicates that the requirement (1a) cannot be met. For the case in question, these indicators have values:

– exact compensation of cable capacity, FSR

$$a_{Q\,\max} = 16.14\%\,, \quad a_{Q\,\min} = 10\%\,,$$

– step adjustment of the reactor, VSR

$$a_{Q\,\max} = 10.4\%\,, \quad a_{Q\,\min} = 2.8\%\,.$$

As can be seen, the regulated reactor provides greater possibilities to meet the operator's requirements in terms of readiness for generation/absorption of reactive power in the maximum range, although it is undoubtedly more expensive. The decision problem of what reactor to install is deepened by the fact that the lack of readiness to meet the requirement (1a) is not subject to pre-imposed financial penalization. It may happen that during the year the system operator will not even demand the maximum generation or minimum absorption of reactive power from the PPM operator. On the other hand, if these deficits occur, their systemic effects will burden him severely. It is also possible to exclude the introduction of an obligation to the distribution system operator tariff regarding readiness in the field of generation/absorption of reactive power, or, on the contrary, to treat it as a paid system service.

On the other hand, the financial dimension does not compensate for the reactive power flow through PCC, in the case of zero active power generation – according to the dependence (2). It is particularly severe in the case of an FSR tuned exactly to the capacity of a 110 kV cable, because the annual penalty for the resulting "offsetting" of the considered farm would be about PLN 310 000. In the case of the VSR (Variable Shunt Reactor) with step adjustment, this penalty would significantly decrease to PLN 24 000. If the cost of the FSR for 110 kV voltage of 13 Mvar is about PLN 550 000, then even twice the cost of the VSR reactor justifies its use without conducting complex economic analyses. However, the question of choosing its inductance and the number of taps remains open, which in a significant way translates into the value of investments.

4. Conclusions

When analyzing the consequences of implementing the requirements for wind farms (PPM) included in EU regulation 2016/631, it should be stated that:

– despite the ability of wind farm generators to generate and absorb power in wide limits, it is possible that reactive power deficits occur in both directions (generation and absorption) in relation to the requirements formulated in [3];

– the consequences of the inability to meet these requirements should be additionally determined by the operators (e.g. in the form of financial penalties), which in turn would allow a rational and justified selection of regulatory devices;
– operators should set a certain margin of tolerance in meeting the requirements [3] and the financially restricted requirement of zero flow of reactive power by PCC for lack of active power generation;
– in order to meet the requirements [3], it is necessary for the farm's reactive power generation system to co-operate with a reactor that compensates for a 110 kV cable capacity, which will allow the resignation of the installation of additional sources of reactive power;
– initial assessment indicates economic justification for the use of reactors with the tap regulation under load (VSR).

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