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PROBLEMS OF REACTIVE POWER COMPENSATION OF 110 KV LINE CABLE

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Abstract

Construction of 110 kV cable systems, where the line length exceeds ten kilometers requires compensation of reactive power generated by the cable capacitance. The compensation can be realized with the application of shunt reactors, whose selection seems to be an easy task. The presented considerations deal with a problem, whose source are the below listed facts. Both the 110 kV cable and the shunt reactor to be applied are custom made and their quality parameters are subject to random variability, whose source are manufacturing processes. Construction of a cable system and manufacturing of a customized shunt reactor are realized at the same time and hence it is not possible to have the reactor matching the already existing and tested cable line. Taking into account that cable and reactor parameters are of random character, the shunt *reactor selection process exhibits features of a stochastic process. The article presents the Monte Carlo simulation results obtained for various parameters of the analyzed HV cable line – shunt reactor system. Various forms of the random variable distribution have been obtained and the random variable is the operation compensation costs. The performed analyses make it possible to select optimal inductance for the shunt reactor. The highest value of the probability that operation costs of the reactive power compensation will not exceed a certain predefined value has been assumed as the selection criterion.*

Keywords

Reactive Power Compensation, HV Cables, Wind Farms, Monte Carlo Simulation

1. Introduction

For several years there has been a sharp increase in the number of 110 kV cable lines the length of which is over a dozen of kilometers. Lines which are almost 100 km long can be also found in the systems of European operators. Cable lines of considerable length are very often used to connect wind farms to the power system. The 110 kV cable lines are characterized by a large capacitance of 0,15-0,20 μF/km on average. It means that a line of 10 km in length is the source of reactive power of 6-7,5 Mvar. It is a great power which is the cause of the well-known negative technical consequences (Saadat H, 2010, Lubośny Z, 2003).

Operators of power systems introduce penalty costs in their tariffs charged for transmission of reactive power to the network (PGE 2017). They are very high because the price of the redundant reactive power equals 25%-100% of the analogue price of the active power. At this point, it is worth noting that from a practical point of view, the term "reactive energy" makes no sense. However, such a term is used by engineers to define the reactive power taken at a certain time by measuring devices. That is why the unit of "reactive power" is called Mvarh (megawatt hour). In the case discussed, the penalty costs for one-year work of 110 kV cable without reactive power compensation amounts to one million euro (Lubośny Z, 2003).

Thus, it is obvious that investors are forced to use reactive power compensation. The basic compensation device is a shunt reactor (Figure 1). Shunt reactors for 110 kV voltage of several dozens megavars (Mvar) are relatively expensive devices. Their price considerably varies depending whether the shunt reactor inductance is subject to adjustments and it also depends on the accuracy of this regulation. At the same time, the shunt reactor is a source of energy loss which increases the annual costs of usage. The process of the proper choice of the compensation devise is additionally complicated by the fact that neither the 110 kV cable capacitance not the shunt reactor shunt inductance are parameters whose value is strictly determined. Cables are produced in short series, practically, made to orders placed by particular investors. Also shunt reactors are produced as unit devices. Thus, their basic ratings (cables –C_{nj}, shunt reactors – L_n) are random variables. As a result, compensation devices manufactured according to the data of the designed cable lines will not free an investor from high annual operating costs relating to the "cable-shunt reactor" system (Iwanicki M., Dębek M., 2015).

The tests presented in the article demonstrate a method supporting an investor's decision and provide the answer to the question: what is the upper limit of costs that are worth bearing with respect to a compensation device?

2. Basic Compensation Scheme

Figure 1. presents a sensible scheme: a wind farm (the analysis related to zero power generation), shunt reactor, 110 kV cable, system. The fixed SR was taken into consideration. Figure 2 shows a variable SR ensuring a step adjustment with tap changers. It is also possible to take into consideration a SVC system with a flexible adjustment of reactive power allowing the most accurate degree of compensation.

The existing studies (Saadat H, 2010) suggest that a cable line of several dozens kilometers in length should be modelled as a long cable line with distributed parameters. However, on the other hand, such a line is made as a connection of several cross bonding sections (Sobral A., Moura A., Carvalho M, 2011), each of which can be modelled with a simplified type Π model. As a result, it is possible to use a model with a ladder structure – Figure 1, Figure 2. A model of a power system may be an accurate multi-node model or its equivalent. In case of such a configuration of a model, the choice of L_n inductance of the shunt reactor seems to be a trivial calculation operation: a shunt reactor is considered to be well fitted if for the idle state of the wind farm, at the connection point of the cable line to the system (PCC node, PK measuring point), with rated voltage $U_{PCC}=U_N$, the reactive power flow shows a zero value, i.e. $Q_{PK}=0$. The inductance value of the shunt reactor fitted in this way can be calculated using the formula:

$$L_n = \frac{1}{\omega_n^2 \cdot C_n} \quad (1)$$

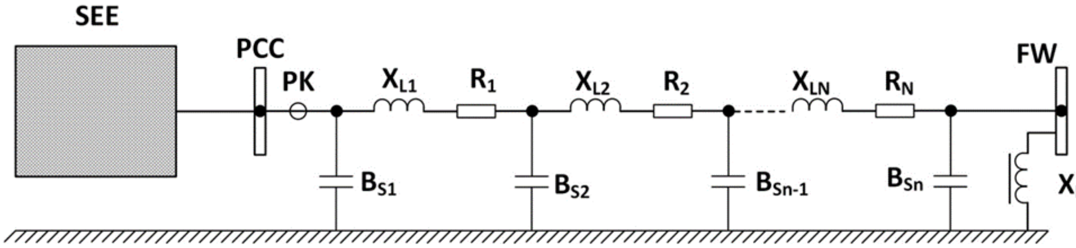

Figure 1: *Calculation model of a cable line taking power from a wind farm (FW) together with a shunt reactor of fixed inductance (Fixed SR)*

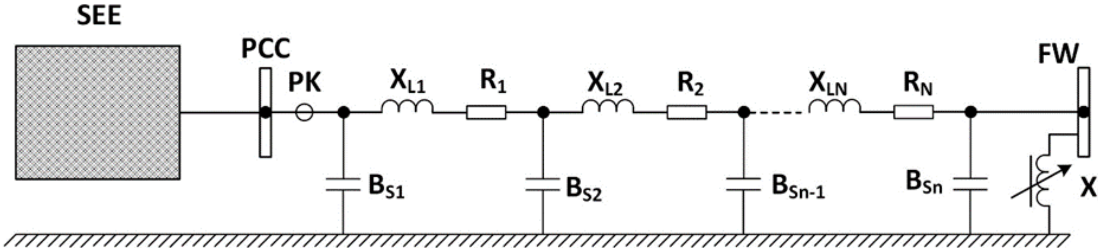

Figure 2: *Calculation model of a cable line taking power from a wind farm (FW) together with a shunt reactor of variable inductance (Variable SR)*

This simple calculation procedure faces some practical obstacles in form of uncertainty whether producers stick to the construction parameters or not – with respect to both the 110 kV cable and shunt reactor as well. Thus, both the value of the cable capacitance and of the shunt reactor inductance might be considered as determined when the cable line has been built and the shunt reactor delivered to the wind farm 110 kV switching station and ultimately assembled. Producers are not very willing to talk about a tolerance in meeting the previously declared parameters, but sooner or later the information on this issue is included in the contract concluded with the investor. Additionally, it should be taken into account that the deadline requirements relating to the investment process make it necessary to simultaneously place orders in both cable producers and shunt reactor producers as well (Kacejko P., Pijarski P, 2009, 2013).

The results of calculations presented in this article were obtained for a cable line l_k=50 km long and unit capacitance of C_{nj}=0,18 mikroF/km.

3. Estimation of HV cable and Shunt Reactor Parameters

Due to the general nature of this article, it was assumed that in case of production of 110 kV cables and also 110 kV shunt reactors, the construction inaccuracies can be defined by a normal distribution. Thus, the cable line unit capacitance C_{nj} can be treated as a random variable, and the probability that its value is lower than or equals c_{nj} is defined by the dependence (2), and its distribution was shown in Figure 3.

$$P\left(C_{\text{nj}} \le c_{\text{nj}}\right) = \Phi\left(\frac{c_{\text{nj}} - C_{\text{nj}}}{\sigma_c}\right) \tag{2}$$

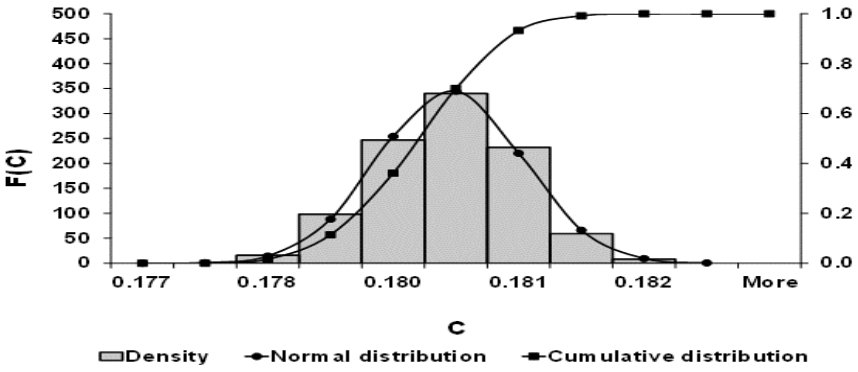

Figure 3: *Cable line unit capacitance* c_{nj} *as a random variable Distribution and cumulative distribution function*

Analogically for the shank reactor, probability that the inductance value L_n is lower than or equals l_n is defined by the dependence (3), and the distribution of the random variable together with the cumulative distribution function is shown in Figure 4.

$$P\left(L_n \le l_n\right) = \Phi\left(\frac{l_n - L_n}{\sigma_L}\right) \tag{3}$$

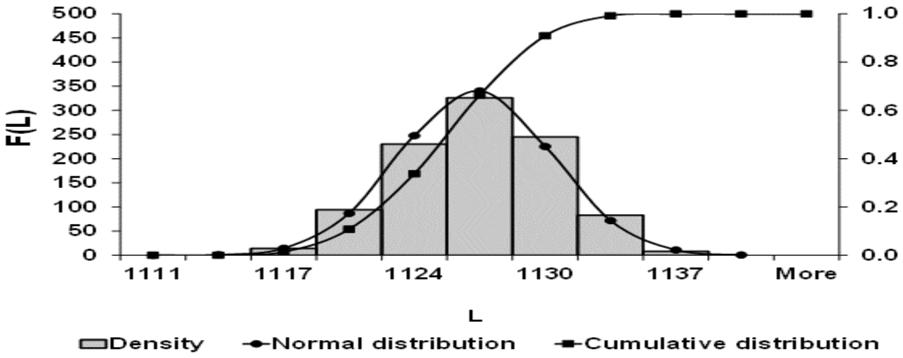

Figure 4: *Shunt reactor inductance L_n as a random variable – distribution and cumulative distribution function*

whereby, in both cases the function Φ denotes the cumulative distribution function of a normal distribution N (0,1), whereas C_{nj} and L_{n} denote the values of 110 kV cable unit capacitance and shunt reactor inductance respectively, assumed by producers as rated values on the grounds of the calculations discussed above. The uncertainty associated with the production processes (of cables and shunt reactor) is expressed by a standard deviation (for a cable and for a shunt reactor respectively). On the grounds of the brief information obtained from the producers, the value =0,03 was assumed (in the authors' of this article opinion - pessimistically) for the cable unit capacitance. It means that the "3-sigma criterion" involves the area of +/-3% in width in relation to the capacitance value assumed to be a rated one.

For the shunt reactor, the standard deviation of the distribution of the inductance value is connected with its price. It was assumed that in case of flexible shunt reactors (FSR) the unit prices are as follows:

EUR 10 000 /Mvar dla $3\sigma_{\mathrm{n}}$ =5%
EUR 15 000 /Mvar dla $3\sigma_{\mathrm{n}}$ =3%
EUR 20 000/Mvar dla $3\sigma_{\mathrm{n}}$ =1,5%.

In case of variable shunt reactors (VSR), they are equipped with taps adjusted in loading conditions (the analysis assumes 9 taps: four upward, four downward and one neutral tap, i.e. +4x1,5%,0,-4x1,5%). The cost of a variable shunt reactor together with the tap changer system was assumed to be EUR 30 000 euro/Mvar, and it allows to obtain the intended inductance values up to 1,5% of rated inductance.

4. Compensation Error – Penalties

The network operator (PSE, PGE, 2017) determines the penalty for consumption or generation of reactive power in conditions of zero generation of active power. For a land farm, the zero generation condition may amount to 2000 - 4000 hours per year. The penalty is calculated in such a way that the reactive power imported or exported as a result of the inaccurate compensation, is treated (irrespective of direction) as the energy taken from the grid by the powered facility, with the penalty coefficient of 0,5 for the 110 kV grid in Poland. It is worth noting that in case of a low voltage grid this coefficient is 1,5. The penalties for consumption/generation of the reactive power in idle work conditions often negatively surprise the investors, because, in spite of the relatively low momentary value, the compensation errors occur for the biggest part of the year.

5. Annual operational cost – results of Monte Carlo simulation

Assuming a random nature of the parameters C_{nj} and L_n,, the effectiveness of the capacitance compensation of a cable line using a shunt reactor of flexible inductance (*FSR*), can be tested with the help of the Monte Carlo simulation. Assuming the distribution probability defined with formulas (2) and (3), the corresponding pair of values (C_{Lj}, L_n) can be randomized with a random numbers generator and the result of such a random selection of the cable unit capacitances and the shunt reactor inductance may be verified by calculations. Due to the random nature of the capacitance and inductance, the penalty for inaccurate compensation is not reduced to zero, although it is reduced considerably in relation the state without compensation. The computational verification also includes the cost of the capital associated with the purchase of the shunt reactor. The analysis assumed the values of the discount factor ranging from 4,5% to 9%. The result showing the total operational costs in the Monte Carlo simulation for 1000 randomized pairs (cable unit capacitance, shunt reactor inductance), was presented in the following way:

$$K_{op} = k_{pn} \cdot e_j \cdot \left| Q_C - Q_L \right| \cdot T_j + \Delta P_L \cdot e_j \cdot T_a + K_{DCF} \qquad (4)$$

where the individual values denote: k_{pn} – penalty coefficient, e_j – price of energy [euro/MWh] ,Q_C – reactive powercaused by capacitance of HV cable [Mvar], Q_L–reactive power available from shunt reactor [Mvar], T_o– “no generation” annual time of the particular wind farm [h/a], ΔP_L–losses of idle status of shunt reactor, T_a= 8760 h, K_{DCF}–reactor, discount cash flow [euro]. For the simulation results presented below, the following indicators were used, apart from the parameters values given above: k_{pn}=0,25-0,5, e_j=50 euro/Mwh, T_j=4000 h/a.

Comparing the four variants in question (marked as i=1,2,3,4) , the following formula was used as the assessment criterion:

$$P\left(K_{op} \leq K_i\right) = 0,9 \qquad (5)$$

The solution which can be recommended to an investor is the one where the costs K_i are the lowest. The figures presented below allow to conclude that for long time of idle work (T_o=4000 h), even the most expensive method of compensation (three times more expensive than the cheapest one) is more profitable than the cheapest one, for which compensation may be inaccurate. These relationships change considerably when the idle work time is short (T_o=2000 h). In such a case, it is better to use a cheapest shunt reactor FSR with big inaccuracy (Fig. 6).

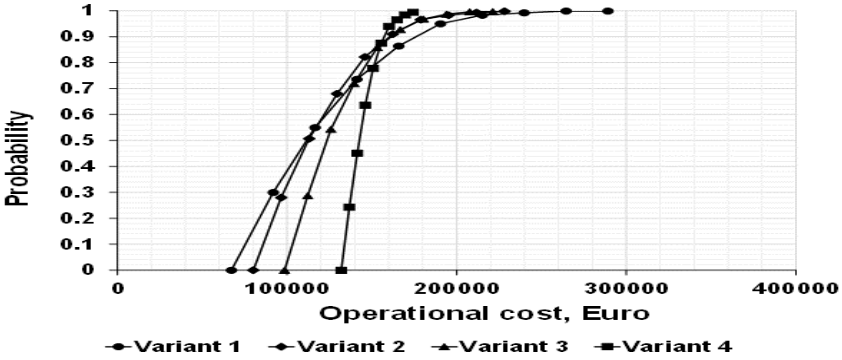

Figure 5: *Operational cost - penalty coefficient equal to 0,5; T_o=4000h, discount factor 9%*

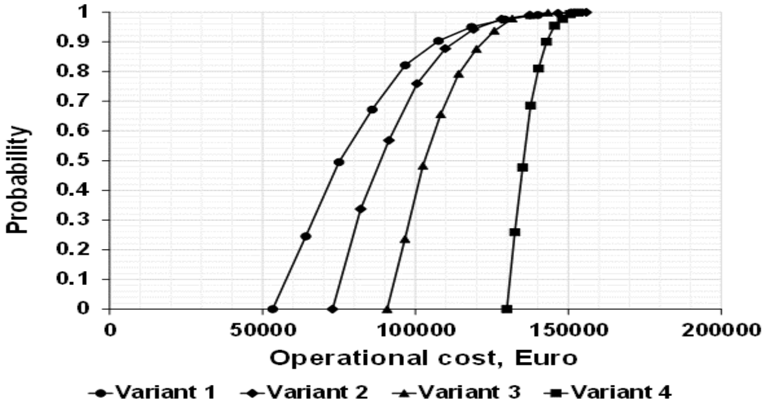

Figure 6: *Operational cost - penalty coefficient equal to 0,5; T_o=2000h, discount factor 9%*

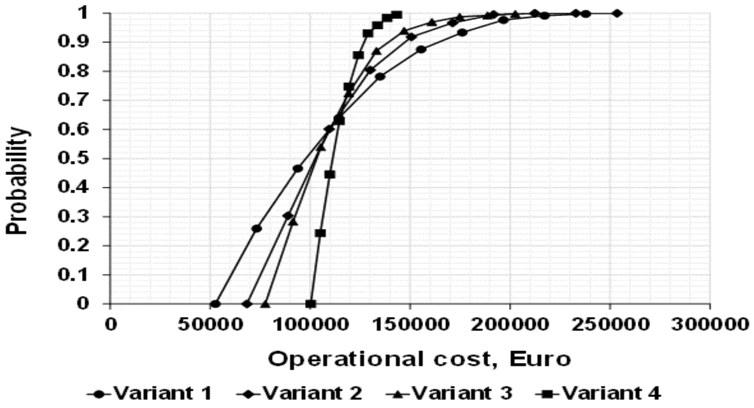

Figure 7: *Operational costs - penalty coefficient equal to 0,5, T_o=4000h, discount factor 4,5%*

6. Conclusion

The Monte Carlo simulation allows to evaluate the random nature of the parameter of the "110 kV cable – compensation shunt reactor" scheme. Depending on the relationships between the figures characterizing the annual cost of compensation, the investor can choose between a cheap shunt reactor which does not ensure accurate compensation and an expensive one considerably increasing its accuracy. The method suggested here can be also extended in order to make a more extensive comprehensive evaluation of the system of reactive power adjustment of a wind farm connected to the PCC point with a long cable line.

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