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The grid element temperature considering when selecting measures to reduce energy losses on the example of reactive power compensation

***Abstract**. Reactive power compensation is one of the leading ways to improve the power transmission efficiency. Currently, there is a problem of increasing the calculations accuracy for compensating devices selection and their application feasibility. The development of smart grids creates an information base that enables refined solution of such problems. We examine one of the ways to increase the accuracy in this work – it is the consideration of temperature dependence of the network resistance elements. In this case, we specify as the optimal values of power compensation devices, as payback periods. Moreover, the clarification for payback period could exceed 100%. We can apply a similar approach to other measures to reduce energy losses, and it opens up an additional field of research. We can use the results obtained in this study both as for power industrial systems, as for urban and rural distribution networks..*

Streszczeni.** W niniejszej pracy rozpatrzono jeden ze sposobów zwiększenia precyzji kompensacji mocy – post temperaturowe zależności oporów elementów sieci. Określone optymalne wartości mocy urządzeń kompensacyjnych na podstawie okresu zwrotu. Podobne podejście można zastosować również do innych metod w celu zmniejszenia strat energii. Wyniki uzyskane w tej pracy, mogą być stosowane w systemach zasilania zakładów przemysłowych, a także w miejskich i wiejskich sieciach rozdzielczych. **Temperaturowe zależności oporów sieci jako metoda redukcji strat energii na przykładzie kompensacji mocy biernej

Keywords:. insulated cables, energy losses, temperature, reactive power compensation.
Słowa kluczowe: kompensacja mocy biernej, straty energii

Introduction

One of the effective directions of energy savings is the reduction of energy losses in grids and increase the transmission capacity of lines [1-2]. There is a standard set of measures to reduce losses. Selecting measures from the set in general includes two stages:

– calculation of optimal exposure (appropriate way of introducing measures);

– feasibility study (the payback period determination).

Refinement of calculations on each step increases the measures introduction efficiency to reduce losses. In its turn, the accuracy is determined with the accepted model of the power supply mode.

We consider the most important parameters that are changed with the introduction of measures to reduce losses [3]. Such parameters include the temperature resistance dependence of the grid active elements [4-7].

We present below specific examples that analyzed the influence of the temperature resistance dependence on the results of the measures selection to reduce losses and the expediency of the parameter consideration. In this case, we determined reactive power compensation as test measures, since, on the one hand, it is the most efficient and widespread measure to reduce energy losses, increase the voltage in the grids and [8-10], on the other hand, when there is reactive power compensation fully reported, both stages of selection are presented..

The calculation of the optimal exposure

Economically justified selection of reactive power sources in the grid is always an optimization problem. The objective function, in general, is a criterion of economic efficiency, more often they are reduced costs; in particular cases, we can use power losses or active power losses instead of the reduced costs. Optimization problem is solved in different ways depending on the rated voltage, the grid configuration and types of compensating devices used.

The article deals with the problem of choosing the static capacitor bank (BSC) in the node of non-branching grid of 10 kV (Fig. 1) on the minimum reduced costs parameter. The task allows getting results easy to analyze.

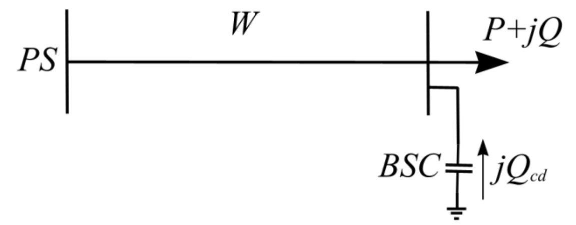

Figure 1 – Non-branching grid: P, Q are active and reactive powers of the load; Q_{cd} is reactive power of the compensating device (high-voltage BSC); PS is power supply

Selecting only the high-voltage BSC is also due to simplify the problem as when choosing BSC 0.4 kV then we need except 10 kV grid to consider another grid element: the transformer 10/0.4 kV. In fact, if the load comprises both low voltage and high-voltage components then we are to choose compensating devices for both voltages classes. However, we can present that if there is optimal choice of high-power BSC then low-voltage BSC in the first approximation does not depend on 10 kV grid parameters, and it is determined only with the ratio of the specific costs and own losses of BSC 10 and 0.4 kV and transformer parameters. Therefore, the task of low and high voltage BSC selection can be accepted conditionally independent. In this case we assume that the low-voltage BSC are already selected.

The task function (reduced annual costs [11, 12]) to select BSC can be approximately written in the form:

$$A = E_n F + M = (E_n + a_r)K + C_e T\left(\Delta P_g + \Delta P_{cd}\right) = \tag{1}$$
$$= (E_n + a_r)K + C_e T\left(\frac{P^2 + (Q - Q_{cd})^2}{U^2} R + p_{sp} Q_{cd}\right)$$

where: F – is investment for the BSC installation; E_n – is investment reduction coefficient; M – is annual operational costs; a_r – is rate of annual deductions for repairs, maintenance and depreciation of the equipment; C_e – is the cost of electricity; ΔP_g , ΔP_{cd} – are power losses in the grid and BSC; T – is integrating factor, transforming power losses into energy losses and having the time dimension; U – is the grid voltage; R – is the grid active resistance; p_{sp} – is specific active power losses in BSC.

Without considering the resistance temperature dependence the equation for calculating the BSC optimal power $Q_{cd,opt}$ is

$$\frac{\partial A}{\partial Q_{cd}} = (E_n + a_r)\frac{\partial F}{\partial Q_{cd}} - 2C_e T \frac{Q - Q_{cd,opt}}{U^2} R + C_e T p_{sp} = 0 \tag{2}$$

When considering the resistance temperature dependence the last is a variable value, and corresponding derivative is introduced into the equation:

$$\frac{\partial A}{\partial Q_{cd}} = (E_n + a_r)\frac{\partial F}{\partial Q_{cd}} - 2C_e T \frac{Q - Q_{cd,opt}}{U^2} R + C_e T \frac{P^2 + (Q - Q_{cd,opt})^2}{U^2}\frac{\partial R}{\partial Q_{cd}} + C_e T p_{sp} = 0 \tag{3}$$

The resistance derivative of the BSC power is negative (when increasing Q_{cd} the grid is discharged and the cables temperature is reduced, it leads to decrease in active resistance). As a result, there is a tendency to increase the BSC optimal power calculated according to equation (3), as compared with the calculation according to equation (2) (except in some cases where there are both low load and low ambient temperature).

There are the results of calculations of BSC optimal capacity for SAX-50 and SAX-240 cables of different lengths. The temperature calculation was conducted by the following mathematical model of the insulated cable thermal mode [13]:

$$\Delta p'_0\,(1 + \alpha\Theta_{sur}) = d_c \begin{bmatrix} \pi\alpha_c(\Theta_{sur} - \Theta_{amb}) + \\ + \pi\varepsilon C_0\left(T_{sur}^4 - T_{amb}^4\right) - A_s q_s \end{bmatrix}$$

$$\Theta_{sur}^{[k+1]} = \Theta_{amb} + \left[\frac{\sqrt[4]{d_c}}{0.749\pi}\sqrt{\frac{T_{amb}}{P}}\begin{pmatrix} \frac{\Delta p'_0}{d_c}\left(1 + \alpha\Theta_{sur}^{[k]}\right) - \\ - \pi\varepsilon C_0\left(T_{sur}^{[k]4} - T_{amb}^4\right) + \\ + A_s q_s \end{pmatrix}\right]^{0.8} \tag{4}$$

$$\Theta_{sur}^{[k+1]} = \Theta_{amb} + \left[\frac{1}{\pi\alpha_c}\begin{pmatrix} \frac{\Delta p'_0}{d_c}\left(1 + \alpha\Theta_{sur}^{[k]}\right) - \\ - \pi\varepsilon C_0\left(T_{sur}^{[k]4} - T_{amb}^4\right) + A_s q_s \end{pmatrix}\right]^{0.8}$$

where: $\Delta p'_0$ – is active power losses in the conductor per length unit at Θ_{sur} = 0 ºC; d_c is – diameter of the conductor; α_c is a coefficient of heat transfer with convection; Θ_{amb} – is ambient temperature (°C); ε – is the emissivity of the conductor surface; C_0 is radiation coefficient of blackbody; T_{sur} – is the temperature of the outer surface of the insulation *(K); T_{amb}* – is ambient temperature (K); A_s –is the absorption capacity of the surface for solar radiation; q_s – is flux density of solar radiation on the conductor; k_v is coefficient taking into account the wind direction; v is wind speed; k – is number of iteration.

Baseline data for calculations, except for the grid length and load powers are shown in tables 1, 2.

Table 1.Cable parameters

Cable	SAX-50	SAX-240
Chase resistance at 20 ºC, Ohm/km	0.72	0.145
The core radius, mm	4	9.05
The outer radius, mm	6.35	11.4

Table 2. Other data

The parameter name and designation	The numerical value
Insulation thermal conductivity coefficient λ_{ins}	0.38 W/(m·K)
Temperature coefficient of resistance α	0.0043 ºC-1
The degree of the cable surface emissivity ε_n	0.8
The absorption capacity of the cable surface for sunlight A_s	0.9 (the approximate value)
Ambient temperature Θ_{amb}	0 ºC
The atmospheric pressure P_{atm}	100000 Pa
The wind speed V	1 m/s
Coefficient of the wind attack angle k_V	0.5
The direct solar radiation flux density to the surface perpendicular to the sun's rays $q_{s,cabl}$	500 W/m2
The diffuse solar radiation flux density $q_{s,diff}$	100 W/m2
The coefficient considering the shadiness of the grid areas k_{sh}	0.6
The angle between the cable axis and the direction of sun rays φ_s	45º
The integrating factor transforming power losses into energy losses, T	5000 h
The cost of electricity C_e	2.098 rub/(kW·h)
Investment reduction coefficient $E_н$	0.14 1/year
The rate of annual deductions for repairs, maintenance and depreciation of electrical equipment a_r	0.059
Specific active power losses in BSC p_{sp}	0.002 kW/kvar

As a reactive power source we used BSC type UKL-56 with rated voltage of 10.5 kV. The search for optimal power was conducted with reduction that the voltage does not change in the load node. Considering the cable heating calculations we used resistance reduced to 20 ºC. Considering heating resistances were simulated with temperature dependence $R=R_0(1+\alpha\Theta_{cable})$ [14-17]. The calculation results are summarized in tables 3, 4.

Table 3. BSC optimal POWER for SAX-50 cable at load powers P=3300 kW, Q=2500 kvar

The grid length, m	Q_{cd}, kvar	BSC cost, rub	A, rub		$Q_{cd,opt}$, kvar	
			Without considering heating	Considering heating	Without considering heating	Considering heating
190	900	169448	89339	282008*	900	1350
	1350	215232	90132	275248		
300	1350	215232	101119	393407	1350	1350
400	1350	215232	111110	500825	1800	1800
	1500	258892	113202	498897		
	1800	270869	106470	486385		
650	1800	270869	115723	733083	1800	2250
	2250	329574	115859	725705		

***** Big difference in the cost, obtained with and without considering heating, is mainly due to the fact that when calculating without considering heating we excluded the power loss cost from the costs determined with active power transfer (like a constant value), while calculating considering heating we considered it (as its value is changed when we change the resistance).

Table 4.BSC optimal POWER for SAX-240 cable at load powers P=9500 kW, Q=6700 kvar

The grid length, m	Q_{cd}, kvar	BSC cost, rub	*A*, rub		$Q_{cd,opt}$, квар	
			Without considering heating	Considering heating	Without considering heating	Considering heating
330	1800	270869	212173	789892	1800 or 2250	2700
	2250	329574	212179	778129		
	2700	391406	214840	772873		
520	3150	449769	255264	1122727	3150	4000
	4000	575722	256145	1105622		

All calculations, the results being shown in the tables, correspond to the large load of the grid (when there is no BSC the cable temperature is close to the maximum, but it does not exceed it). The tables show that considering heating gives either the same BSC optimal power, which is obtained without heating or power, on one, maximum two standard steps more. Since the standard stages are large enough, then the difference of optimal capacity can be large. On average according to the tables the optimal power specification obtained considering heating, towards the powers obtained without heating is 22.5%.

It should be noted that the objective function near the optimal point has flat nature. As a result, a significant refinement of optimal capacities does not lead to an equally large economic effect. For example, the cost reduction given in Table IV is around 17,000 rubles/year. This value represents an additional economic effect caused by only considering heating; the effect measure introduction in general is much greater. In other words, the savings of 17,000 rubles is achieved only with change in the method of calculation that still allows considering it effective. Furthermore, it relates to a single grid, but not to the network in whole.

Increasing the optimal capacities due to considering heating, leads to additional discharge of grids and, consequently, to improve the temperature mode of its elements. We can consider it as a relevant positive technical effect.

Determining the payback period

The payback period measures to reduce energy losses can be objectified as follows:

$$T_{pd} = \frac{F}{M_{in} - M_{aft}} = \frac{F}{M_{d,in} - M_{d,aft} + C_e\left(\Delta W_{in} - \Delta W_{aft}\right)} \quad (5)$$

where M_{in} , M_{aft} – are annual operating costs, respectively at the initial mode and after introducing measures;

$M_{d,in(aft)}$ – are components of the costs of depreciation, repairs and maintenance of equipment;

ΔW_{in} , ΔW_{aft} – are energy losses in the initial mode and after introducing measures.

The denominator of formula (5) includes the difference of energy losses in the initial mode and after introducing measures. If the error of loss calculation vary ($\delta\Delta W_{in} \neq \delta\Delta W_{aft}$), then the error of their reminder calculation can be very large: $\delta(\Delta W_{in} - \delta\Delta W_{aft}) >> \delta\Delta W_{in(aft)}$. Accuracy for calculating the payback period in most cases will be even more as there is difference in the costs of depreciation, repair and maintenance of equipment - the value is usually negative.

These conditions occur when we ignore factors that are changed as a result of introducing measures. In particular, these factors include the temperature and the grid elements.

With respect to the problem under consideration of reducing energy losses without considering heating is

$$\Delta W_{in} - \Delta W_{aft} = T\left[\frac{P^2+Q^2}{U^2}R - \frac{P^2+\left(Q-Q_{cd}\right)^2}{U^2}R - p_{sp}Q_{cd}\right] = T\left[\frac{2QQ_{cd}-Q_{cd}^2}{U^2}R - p_{sp}Q_{cd}\right]. \quad (6)$$

Here we have used the simplifying assumption that the integrating multiplier for losses in the lines and BSC is the same. The same assumption is used in the calculation of the BSC optimal capacities.

Reduction of losses considering heating is

$$\Delta W_{in} - \Delta W_{aft} = T\left[\frac{P^2+Q^2}{U^2}R_{in} - \frac{P^2+\left(Q-Q_{cd}\right)^2}{U^2}R_{aft} - p_{sp}Q_{cd}\right] \quad (7)$$

where R_{in} , R_{aft} are the grid resistances in the initial mode and after BSC introduction, they differ due to temperature dependence, moreover $R_{in} > R_{aft}$.

The last formula shows that when there is BSC installing the energy loss are reduced not only due to the actual decrease in transmitted reactive power, but also by reducing the resistance. Besides losses for transmission active power are reduced, and not only reactive power. Calculation without considering the temperature does not allow taking into account these additional factors.

We present in tables 5 and 6 the results of payback periods calculation for optimal BSC power corresponding Tables III and IV. In addition, for each BSC we calculated the payback period when there is outdoor installation without the northern container T_{amb} and in the northern container $T_{amb,north}$. The tables show that the payback period, some determined with and without heating, much differ from each other. For the cases examined, the minimum error in determining the payback period, due to the neglect of heating is 37.2%, the maximum is 212%, while the average according to the tables is 95.2%. Thus, the error is determined commensurate with the determined value. It demonstrates the need for considering heating factor in the calculation of payback periods at least at high loads of the grid elements.

In all these cases, the payback period error calculation is positive. It means that if without heating the introduced measure is characterized as non-profitable, then if we consider heating it can go into the category of profitable (see, e.g., Table VI, length 330 m, northern container used). Implementation of this measure will lead, in addition to the actual reduction of losses, to an additional grid discharge. So, there is the same technical effect from considering heating as in the calculation of optimal BSC capacities - improving temperature mode of the grid elements.

Table 5. The payback period for bsc installing for sax-50 cable at load powers p=3300 kw, q=2500 kvar

The grid length, m	Calculation without considering heating					Calculation considering heating				
	Qcd,opt, kvar	BSC cost, rub		T_{amb}, year	$T_{ambnorth}$, year	*Qcd,opt*, kvar	BSC cost, rub		T_{amb}, year	$T_{amb,north}$, year
		Without north container	in north container				Without north container	in north container		
190	900	169448	336182	7.04	23.6	1350	215232	411879	3.26	7.57
300	1350	215232	411879	3.05	6.98	1350	215232	411879	1.68	3.54
400	1800	270869	495364	2.25	4.63	1800	270869	495364	1.31	2.56
650	1800	270869	495364	1.18	2.3	2250	329574	580029	0.86	1.57

Table 6.The payback period for bsc installing for sax-240 cable at load powers p=9500 kw, q=6700 kvar

The grid length, m	Calculation without considering heating					Calculation considering heating				
	Qcd,opt, kvar	BSC cost, rub		T_{amb}, year	$T_{ambnorth}$, year	*Qcd,opt*, kvar	BSC cost, rub		T_{amb}, year	$T_{ambnorth}$, year
		Without north container	in north container				Without north container	in north container		
330	1800	270869	495364	5.3	13.1	2700	391406	663691	2.71	5.18
	2250	329574	–	5.6	–*					
520	3150	449769	754020	2.76	5.21	4000	575722	910783	1.73	2.9

* The payback period was not calculated, as this capacity when installed in the northern container is not optimal.

.Conclusion

The article examines the problem of considering the grid elements heating factor (temperature dependence of resistance) at reactive power compensation. Theoretical calculations and calculation examples show that the considering fact helps to clarify as the optimal BSC capacity as payback period. Optimal capacities for large grid elements loads are specified by approximately 20%, which is accompanied with a certain economical effect. However, the main effect is observed when calculating the payback timing when large loads are specified by about 100%. In addition, considering heating at reactive power compensation improves temperature mode of grid elements.

As discussed selection stages (calculation of the optimal exposure and determining the payback period) are not only to reactive capacity compensation, but also to other measures to reduce energy losses, characterizing with similar laws, the conclusions drawn in the first approximation can be extended also to other measures.

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REFERENCES

[1] Jana Heckenbergerová, Petr Musilek, Konstantin Filimonenkov, "Quantification of gains and risks of static thermal rating based on typical meteorological year" International Journal of Electrical Power & Energy Systems, Volume 44, Issue 1, January 2013, Pages 227-235.
[2] A.A.P. Silva, J.M.B. Bezerra, " Applicability and limitations of ampacity models for HTLS conductors" Electric Power Systems Research, Volume 93, December 2012, Pages 61-66.
[3] A. Kuppurajulu, S. Elangovan, T. Krishnaparandhama P. Subramaniam , " Method for reducing losses in distribution feeders " International Journal of Electrical Power & Energy Systems, Vol. 3, Issue 4, October 1981, Pages 193-196.
[4] V. Cecchi, A. S. Leger, K. Miu and C. O. Nwankpa, "Incorporating Temperature Variations Into Transmission-Line Models," in IEEE Trans. on Power Delivery, vol. 26, no. 4, 2189-2196,
[5] V. Cecchi, M. Knudson, and K. Miu. "System Impacts of Temperature-Dependent Transmission Line Models," on IEEE Trans. on Power Delivery, vol. 28, no.4, 2300-2308, 2013.
[6] AAP Silva ,JMB Безерра, "Applicability and limitations of ampacity models for HTLS conductors" Electric Power Systems Research, vol. 93, December 2012, pp/ 61–66.
[7] H. Kocot , P. Kubek "The analysis of radial temperature gradient in bare stranded conductors,"Przegląd Elektrotechniczny, vol. 10, pp. 132–135, 2017.
[8] Abdullah M. Shaheen, Ragab A. El-Sehiemy, Sobhy M. Farrag, "A novel adequate bi-level reactive power planning strategy" International Journal of Electrical Power & Energy Systems, Volume 78, June 2016, Pages 897-909.
[9] M.S. Rahman, M.A. Mahmud, A.M.T. Oo, H.R. Pota, M.J. Hossain, " Agent-based reactive power management of power distribution networks with distributed energy generation" Energy Conversion and Management, Volume 120, 15 July 2016, Pages 120-134.
[10] Y. Sayenko , T. Baranenko , D. Kalyuzhniy, " Kompensacja mocy biernej w systemach zasilających duże zakłady przemysłowe" Przegląd Elektrotechniczny, vol. 11, 77–80, 2015.
[11] Idel'chik, V. I. Electric systems and networks: Textbook for Universities / V. I. Idel'chik. , M. : Energoatomizdaat, 1989., 592
[12] V. Goryunov, S. Girshin, E. Kuznetsov, A. Bigun, E. Petrova, A. Lyashkov, " Optimal sizing of capacitor banks to reduce power losses with accounting of temperature dependence of bare overhead conductors", SMARTGREENS 2017 - proceedings of the 6th international conference on smart cities and green ICT systems; 2017. 174 p
[13] S.S. Girshin, V.N. Goryunov, E.A. Kuznetsov, E.V. Petrova, A.A. Bubenchikov, and D.V. Batulko, "Thermal Rating of Overhead Insulation-Covered Conductors in the Steady-State Regime", MATEC Web of Conferences, vol. 70, 2016
[14] V. N. Goryunov, S. S. Girshin, E. A. Kuznetsov, E. V. Petrova, A. Ya. Bigun, "A mathematical model of steady-state thermal regime of insulated overhead line conductors", In Proc. 16th IEEE Int. Conf. Envir. and Electr. Eng., Florence, Italy, 2016.
[15] .S.S. Girshin, A.A. Bubenchikov, T.V. Bubenchikova, V.N. Goryunov, and D.V. Osipov, "Mathematical model of electric energy losses calculating in crosslinked four-wire polyethylene insulated (XLPE) aerial bundled cables", In Proc. 11th IEEE Int. Conf. ELEKTRO, Strbske Pleso, Slovakia, 2016, pp. 294-298.
[16] Cigr´e Working Group 22.12, "Thermal behaviour of overhead conductors," Cigr´e Brochure 207, Aug. 2002.
[17] IEEE, "Standard for calculating the current temperature of bare overhead conductors, Std 738," 2006.