Optimal Sizing of Capacitor Banks to Reduce Power Losses
With Accounting of Temperature Dependence of Bare Overhead Conductors

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Abstract: In carrying out a reactive power compensation it is necessary to select the powers of compensation units for minimizing the active power losses as well as minimize financial losses of installing the reactive power compensation units. Thus, there is a multi-factor optimization problem for sizing of reactive power compensation devices. The paper studied the effect of bare overhead conductors heating to the optimal choice of measures to reduce electricity losses by the example of reactive power compensation. We describe two stages in the selection of reactive power compensation devices and their clarification considering the grid elements temperature. We determine the economic efficiency calculations results of using reactive power compensation as measures to reduce losses in grids, with and without the grid elements temperature dependence consideration. We consider the data on the optimal choice of compensating devices and payback period determination depending on the load, the conductor type and the grid length. The research results can be applied in the optimization of existing systems and in the design of power supply systems of enterprises to reduce the active power losses with the minimal cost of compensation units.

1 INTRODUCTION

One of the major problems in the power sector is to reduce the power losses in grids. The grid comprises generating, supply mains, distribution mains and loads. The power loss in the distribution systems may reach 13% (Isac et al., 2013) resulting in significant economic loss. Power loss is reduced due to the special measures introduction (Kalambe and Agnihotri, 2014). The measure is reactive power compensation in distribution grids (Mohsin, 2016).

The measures choice in the general case involves two stages:

– calculation of the optimal effect (optimal way of measure introduction);

– feasibility study (the payback period determination).

Calculations refinement on each of these stages increases the measures introduction efficiency to reduce losses. The compensating device sizing and installation position are the problem of the measure introduction optimal way. There are a number of methods for the accurate selection of the compensating device. There were developed advanced techniques like genetic algorithms (Haghifam and Malik, 2007), (Da Silva et al., 2000) fuzzy logic (Das, 2008) and artificial neural networks (Rao et al., 2013), (Das and Varma, 2001) to solve the problems. The presented methods accurately solve tasks and consider the load variability, but they do not consider the detailed analysis of the parameters that affects the power loss level. We assume that the most significant point is to consider the options which are a function from the introduced measures to reduce losses. Such parameters include the temperature dependence of the grid active elements resistance (Girshin et al., 2016), (Morgan, 1982), (CIGRE, 2002), (IEEE, 2012).

The purpose of this article is to prove that the compensating devices optimal choice problem can be successfully achieved with increase in the accuracy of the power loss determining. Considering real temperature of overhead conductors will increase the power loss accuracy, and thus the compensating device choice accuracy as well. This article explains how to choose capacitor banks in the single-path distribution mains node on the minimum

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reduced costs criterion.

Section 2 describes the optimal sizing problem formulation for compensating devices with accounting of grid elements temperature. We consider Section 3 on the compensating device optimal selection issues by the example of capacitor banks; we determine a bare conductor thermal model. There is methodology for calculating the payback period of the capacitor banks installation considering the temperature dependence of the conductor resistance. We consider Section 4 on the example of the capacitor banks choice according to the proposed method. We determine Section 5 on the main findings confirming the need to consider the effect of the conductor heating when choosing compensating devices.

2 PROBLEM FORMULATION

The power loss in grids is divided into active power loss and reactive power loss that are written with Equations 1, and 2 (Reddy, 2015):

$$\Delta P = I^2 R \tag{1}$$

$$\Delta Q = I^2 X \tag{2}$$

where ΔP is active power loss, ΔQ is reactive power loss, I is current in the grid, R is active resistance of the transmission line, X is inductive reactance of the transmission line.

The current in transmission line can be calculated according to Equation 3

$$I = \frac{P - jQ}{U} \tag{3}$$

where P, Q are active and reactive powers in the line, U is voltage at the beginning of the grid.

Reactive power Q considering compensation (Figure 1) is defined with Equation 4:

$$Q = Q_{old} - Q_c \tag{4}$$

where Q_{old} is reactive power in the grid before the compensating device installation, Q_c is reactive power compensating device.

As follows from Equations 1-4 power compensating device depends on the power losses in the overhead line, and hence on the grid active resistance.

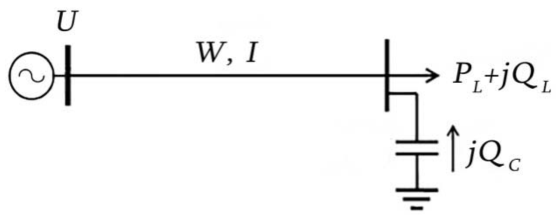

Figure 1: Single-path distribution network: P_L, Q_L are active and reactive power loads, W is energy transmitted along the grid.

Dependence of active conductor resistance and active power losses on the conductor temperature can be represented by Equations 5, and 6 (IEEE, 2012):

$$R_t = R_{20}(1 + a(t_c - 20)) \tag{5}$$

$$\Delta P_t = I^2 R_t = I^2 R_{20}(1 + \alpha(t_c - 20)) \tag{6}$$

where R_t and R_{20} are active resistances accordingly when the conductor temperature is t_c and 20 ^{0}C, α is temperature coefficient of active conductor resistance.

The error in determining the resistance and the active power and energy losses depending on the conductor temperature relative to the data are determined with the Equation 7:

$$\delta = \frac{R_{20} - R_{20}(1 + \alpha(t_c - 20))}{R_{20}} 100\% = \alpha(t_c - 20)100\% \tag{7}$$

We represent in Table 1 the uncertainty range of active power loss determined excluding changes in conductor temperature.

The accuracy for high-temperature conductors with transmission capacity can reach 104%. Significant values of errors are feasibility evidence of considering the actual conductor temperature to improve existing methods of electric energy losses calculation in the overhead power lines.

However, the practical interest is not only to increase the calculation accuracy but to decrease the degree of losses due to the appropriate measures selection.

Table 1: The uncertainty range of active power losses determined excluding changes in the conductor temperature.

Type of conductor	Operating temperature, ºC	Uncertainty range of losses, %
Bare overhead conductors	from -50 to +90	56
Overhead insulation-covered conductors	from -50 to +70	48
High-temperature conductors with increased transmission capacity		
TACSR/HACIN	from -50 to +210	104
TACSR/ACS	from -50 to +150	80
GTACSR	from -50 to +150	80
ACCR	from -50 to +210	104

3 OPTIMAL SIZING OF REACTIVE POWER COMPENSATION DEVICES

3.1 Selection of Compensating Devices by Considering Thermal Dependencies

The optimization task can be solved on the basis of the objective function A for reduced costs per annum (Idelchik, 1989) in accordance with Equation 8

$$A = E_n F + M = \left(E_n + a_r\right) F + C_e T\left(\Delta P_t + \Delta P_c\right)$$
$$= \left(E_n + a_r\right) F + C_e T\left(\frac{P^2 + \left(Q - Q_c\right)^2}{U^2} R + p_{sp} Q_c\right) \quad (8)$$

where F is investment for the installation of capacitor banks, E_n is capital reduction coefficient, M is annual operational costs; a_r is rate of annual deductions for repairs, maintenance and depreciation of electrical equipment, C_e is the electricity cost, ΔP_c, ΔP_t are power loss in capacitor banks and in overhead line, T is integrating factor transforming power loss into energy loss and it has the time dimension, p_{sp} is specific losses of active power in the capacitor banks.

Without considering the temperature dependence of the resistance the equation for calculating the capacitor banks optimal power $Q_{c,opt}$ is described with Equation 9

$$\frac{\partial A}{\partial Q_c} = \left(E_n + a_r\right)\frac{\partial F}{\partial Q_c} - 2C_e T\frac{Q - Q_{c,opt}}{U^2} R$$
$$+ C_e T p_{sp} = 0 \quad (9)$$

Resistance considering temperature is variable, and corresponding derivative is introduced in Equation 10:

$$\frac{\partial A}{\partial Q_c} = \left(E_n + a_r\right)\frac{\partial F}{\partial Q_c} - 2C_e T\frac{Q - Q_{c,opt}}{U^2} R +$$
$$+ C_e T\frac{P^2 + \left(Q - Q_{c,opt}\right)^2}{U^2}\frac{\partial R}{\partial Q_c} + C_e T p_{sp} = 0 \quad (10)$$

Analysis of Equations 9, and 10 shows that the capacitor banks optimal power determined with Equation 10 must be greater than the capacitor banks power defined with Equation 9. This fact is due to the negative value of the resistance derivative according to power dR/dQ_c. Indeed, when increasing Q_c the grid is discharged; so the temperature and hence the conductor resistance are reduced. An exception case is when there is low-temperature environment and the same time there is low grid load. But in terms of the losses value, this case is not worth of detailed consideration.

Temperature calculations are made on the basis of the heat balance equation for bare conductors (Goryunov et al., 2016) in accordance with Equation 11

$$I^2 R_{20}(1 + \alpha(t_c - 20)) =$$
$$= d_c\left[\pi\alpha_c(t_c - t_{amb}) + \pi\varepsilon C_0(T_c^4 - T_{amb}^4) - A_s q_s\right] \quad (11)$$

where t_{amb} is ambient temperature ºC; d_c is the conductor diameter; α_c is coefficient of heat transfer with convection calculated according to the criteria of heat transfer processes similarity, ε is conductor surface emissivity; C_0 is constant of blackbody radiation; T_c and T_{amb} are the absolute temperatures of the conductor and the environment (K); A_s is the absorption capacity of the conductor surface for solar radiation; q_s is solar radiation flux density.

The temperature of bare overhead conductors can be defined while solving of Equation 11 with an iterative method in accordance with Equation 12 (Girshin et al., 2016):

$$t_c^{[k+1]} = t_{amb} + \left[\frac{1}{\pi \alpha_c} \left(\frac{\Delta p_0'}{d_c} \left(1 + \alpha t_c^{[k]} \right) - \pi \varepsilon C_0 \left(T_c^{[k]4} - T_{amb}^4 \right) + A_s q_s \right) \right]^{0.8} \quad (12)$$

where k is number of iteration.

3.2 Calculation of the Payback Period

The second stage implementation results to determine the payback period of the introduced measures to reduce the energy losses can be estimated using Equation 13:

$$T_{pb} = \frac{F}{M_{in} - M_{aft}} = \frac{F}{M_{d,in} - M_{d,aft} + C_e \left(\Delta W_{in} - \Delta W_{aft} \right)} \quad (13)$$

where M_{in} and M_{aft} are annual operating costs, respectively, in the initial mode and after introducing measures, $M_{d,in}$ is components of the costs for depreciation, repairs and maintenance of equipment in the initial mode, $M_{d,aft}$ are components of depreciation, repairs and maintenance costs of the equipment after introducing measures, ΔW_{in} and ΔW_{aft} are energy losses in the initial mode and after introducing measures.

The analysis of Equation 13 shows:

1. If the calculation errors $\delta(\Delta W_{in})$ and $\delta(\Delta W_{aft})$ are not the same, then the inequality is:

$$\delta(\Delta W_{in} - \Delta W_{aft}) >> \delta \Delta W_{in} \quad (14)$$

$$\delta(\Delta W_{in} - \Delta W_{aft}) >> \delta \Delta W_{aft} \quad (15)$$

2. The error of defining the deadline for payback period T_{pb} for most cases will be larger as the difference ($M_{d,in} - M_{d,aft}$) is usually negative.

3. The first two conditions occur when the grid element temperature is not considered but it changes due to measure introduction results.

Reducing the power losses after power factor correction, with and without considering the heating is determined with Equations 16, and 17. We note from Equation 16 that if we consider the temperature then electric power loss decreases for the following reasons:

1. By reducing the transmitted reactive power;
2. By reducing the resistance;
3. By reducing transmission losses of active power.

$$\Delta W_{in} - \Delta W_{aft} = = T \left[\frac{P^2 + Q^2}{U^2} R - \frac{P^2 + \left(Q - Q_c \right)^2}{U^2} R - p_{sp} Q_c \right] = = T \left[\frac{2QQ_c - Q_c^2}{U^2} R - p_{sp} Q_c \right] \quad (16)$$

$$\Delta W_{in} - \Delta W_{aft} = = T \left[\frac{P^2 + Q^2}{U^2} R_{in} - \frac{P^2 + \left(Q - Q_c \right)^2}{U^2} R_{aft} - p_{sp} Q_c \right] \quad (17)$$

where R_{in}, R_{aft} are grid active resistances before and after the input of capacitor banks which have different values due to considering the temperature dependence, besides $R_{in} > R_{aft}$.

Equation 16 recorded by assuming the resistance regardless of the temperature cannot consider these factors. Despite the positive use of the capacitive banks in terms of losses reduction, it is necessary to evaluate the payback period for the capacitor banks optimal power.

4 NUMERICAL EXPERIMENT

The optimal choice of the compensating devices parameters and timing payback period are conducted on the example of a single-path grid shown in Figure 1, with capacitor bank for rated voltages of 10.5 kV. Research conditions are shown in Table 2.

In the first stage we solve the problem of optimal choice of capacitor banks at the node 10 kV on the minimum reduced costs criterion. Selection of only capacitor banks for medium voltage (10 kV) is due to simplify the task, since, in the general case the load is formed with low-voltage (0.4 kV) and medium voltage (10 kV) components, and therefore, it is necessary to select a capacitor bank to both voltage classes. Moreover, we must consider the presence of the transformer 10/0.4 kV. This simplified approach is explained with the independence of the optimal choice of high-voltage and low-voltage capacitor banks. When there is optimal choice of capacitor banks (10 kV) then optimal power of capacitor banks (0.4 kV) is a function of the transformer parameters 10/0.4 kV, as well as the corresponding specific costs and own losses of capacitor banks of both voltage classes.

Table 2: Parameter calculation.

Name and designation of parameters	The numerical values
Value of the conductor resistance: Without heating	Resistance at 20 ^{0}C
Considering heating	Calculated with equation (5)
Chase resistance of AS-50 conductor at 20 ºC, Ohm/km	0.5951
Radius of AS-50 core conductor, mm	4.8
Temperature coefficient of resistance, C^{-1}	0.00403
Emissivity degree of the conductor surface	0.6
Air temperature, ºC	1.7
Atmospheric pressure, Pa	100000
Wind speed, m/s	1
Solar radiation flux density, W/m^2	230
Integrating factor, transforming power loss into energy loss,h	5000
Cost of electricity, rubles/(kW·h)	2.098
Coefficient of bringing investment, 1/year	0.14
Rate of annual deductions for repairs, maintenance and depreciation of electrical equipment	0.059
Specific active power losses in capacitor banks, kW/kVAR	0.002
Voltage in the load node	Does not change
Conductor temperature without capacitor banks	Close to the maximum

The results of studies on the optimal choice of capacitor banks for AS-50 bare conductor with and without considering the conductor heating are shown in Table 3. The calculation without accounting of conductor temperature is classical approach for sizing of capacitor banks (Kalambe and Agnihotri, 2014). Determination of the optimal power increase capacitor banks considering heating $Q_{c,opt,t}$ relative the optimal power without considering heating $Q_{c,opt}$ was carried out according to Equation 18:

$$\varepsilon_1 = \frac{Q_{c,opt,t} - Q_{c,\mathrm{opt}}}{Q_{c,opt}} 100\% \tag{18}$$

We presented in Table 4 the results of payback periods calculation for optimal power of capacitor banks corresponding to Table 3. The calculation of the payback period was performed on Equation 13. The relative differences of defining the payback period due to the neglect of bare overhead conductors heating is calculated according to Equation 19: T

$$\varepsilon_2 = \frac{T_{pb} - T_{pbt}}{T_{pb}} 100\% \tag{19}$$

The analysis of results given in Tables 3 and 4 allows making the following conclusions:

1. The optimal heating power considering the optimal power is either equal to optimal power without heating or exceeds it by one or two nominal values. The mean excess value ε_1, calculated according to Equation 18 and based on Table 3 data is 25%.
2. Presented in Table 4 calculation results according to Equation 19 show that the payback period of compensating devices considering heating may be reduced to 20-65%. These indicators of economic efficiency prove the need to consider heating factor when choosing compensating devices, in particular, when installing capacitor banks.

Table 3: Optimal power of capacitor banks for AS-50 conductors at power load P_L=3300 kW, Q_L=2500 kVAR.

The grid length, m	Q_c, kVAR	Capacitor banks cost, thousand rubles	A, thousand rubles		$Q_{c,opt}$, kVAR		ε_1, %
			Without considering t_c	Considering t_c	Without considering t_c	Considering t_c	
200	900	169.4	220.5	241.8	900	1350	50
	1350	215.2	223.6	240.2			
300	1350	215.2	299.9	324.7	1350	1350	0
	1500	258.9	305.7	328.7			
380	1350	215.2	360.9	392.4	1350	1800	33
	1800	270.9	361.6	387.8			
650	1800	270.9	553.4	598.2	1800	2250	25
	2250	329.6	557.2	597.3			

Table 4: Payback period of capacitor banks installation for AS-50 conductors with load capacities P_L=3300 kW, Q_L=2500 kVAR.

The grid length, m	Calculation without considering t_c		Calculation considering t_c		ε_2, %
	$Q_{c,opt}$, kVAR	T_{pb}, years	$Q_{c,opt,t}$, kVAR	T_{pbt}, years	
200	900	9.8	1350	5.0	48.9
300	1350	4.2	1350	2.6	38.1
380	1350	2.8	1800	2.1	25.0
650	1800	1.5	2250	1.2	20.0

5 CONCLUSIONS

The paper discussed the problem of optimal choice of compensating devices in distribution network. The main originality of suggested approach is considering the bare overhead conductors heating. Numerical results prove the high economic efficient of accounting real conductor temperature while sizing of capacitor banks. In general, the economic effect from the considered measure introduction can be much more by analyzing the grid and improving the thermal mode of the grid due to the load reduction.

Obtained results give capabilities for future researches in the field of reactive power compensation including smart grids and distributed generation systems. One of smart grid features is temperature control of the network elements. Developed algorithm consider the temperature in optimization processes and can be used in smart grids.

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