Economic aspects of reactive power compensation at gas-chemical plant

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Abstract. The use of energy saving technologies, reduction of losses of electric power and the electric power are actual tasks of modern power industry. The cheapest and at the same time the most effective means of increasing the technical and economic indicators of electrical systems is reactive power compensation. The paper considers three variants of reactive power compensation: installation of high-voltage capacitor banks; installation of low-voltage capacitor banks; overexcitation of synchronous machines. The comparative analysis was conducted on models compiled in the program MATLAB Simulink. The costs of generation and transmission reactive power using synchronous motors were defined. The costs of generation and transmission reactive power using low-voltage capacitor banks were defined.

1. Introduction
The use of energy saving technologies, reduction of losses of electric power and the electric power are actual tasks of modern power industry [1–4]. The cheapest and at the same time the most effective means of increasing the technical and economic indicators of electrical systems is reactive power compensation.

It is shown in this work [5], that the well-known model for estimating the reduction of grid organization power losses during reactive power compensation in the network of one of the consumers does not take into account the dynamics of changes in the state of reactive power compensation in the networks of other consumers. Therefore, it is difficult to predict dynamics of changes of revenue side of the project to install a compensating device in the network of investigational consumer during its operation, which increases the extent of risk of projected income generation by investor of reactive power compensation project.

The energy characteristics of AC locomotives can be improved by the way of compensation of reactive power component. Reactive power compensation device consists of a series-connected capacitor (C) and inductance (L), and is connected to the secondary winding of the transformer. The proposed control of the reactive power compensation device is carried out by using and extreme control method [6].

The use of managed devices with sequential compensation is one of the directions of development of managed transmission lines. The influence of controlled devices with sequential compensation on the modes and stability of power system with two generating units is considered. It is revealed that controlled devices with sequential compensation can increase the capacity of the managed transmission lines and have a positive effect on the reserves for static aperiodic and dynamic stability, without leading to instability during compensation [7].
2. Methods
The use of condenser units enables:
- increasing the power factor to the required value;
- reduction of power losses in the elements of the power supply network;
- voltage regulation at various points of the network;
- improving the quality of electricity [8-11].

A gas and chemical plant is powered by DTS-41 (distribution transformer substation), the sections of which are connected to the following loads:
- I section: two high-voltage synchronous motors $P = 600$ kW, one induction motor $P = 320$ kW for a voltage of 6kV, the total low-voltage load $P = 610$ kW, $Q = 300$ kVAR;
- II section: one high-voltage synchronous motor $P=1600$ kW, one high-voltage induction motor $P = 220$ kW, one induction motor $P = 320$ kW for a voltage of 6kV; total low-voltage load $P = 600$ kW, $Q = 300$ kVAR.

The comparative analysis was carried out on the model compiled in the MATLABSimulink program. Model I section is shown in Figure 1.

![Figure 1. Model of I section.](image)

The paper considers three variants of reactive power compensation:
- installation of high-voltage capacitor banks (HCB);
- installation of low-voltage capacitor banks (LCB);
- overexcitation of synchronous machines.

3. Research result
On the model, in the absence of reactive power compensation, $\cos \phi$ on the high and low side was measured. The values of $\cos \phi$ turned out to be equal to:
- on the side 6 $\cos \phi = 0.908$;
- 0.4 $\cos \phi = 0.897$.

Overexcitation of a synchronous motor with a power of 1600 kW was achieved $\cos \phi = 0.95$ on the 6 kV side (initial $\cos \phi = 0.908$) and $\cos \phi = 0.897$ on the 0.4 kV side (initial $\cos \phi = 0.897$). On the low side, $\cos \phi$ has not changed because the 0.4 kV sections receive reactive energy from the 6 kV section.
Using the HCB, the total power consumed by the induction motor \( P = 320 \text{ kW} \), the synchronous motor \( P = 1600 \text{ kW} \), and the total low-voltage load were compensated. As a result, \( \cos \phi = 0.951 \) (initial \( \cos \phi = 0.908 \)) on the side of 6 kV and \( \cos \phi = 0.897 \) on the 0.4 kV side (initial \( \cos \phi = 0.897 \)).

When the reactive power was compensated by the LCB installation, \( \cos \phi = 0.922 \) on the 6 kV side (initial \( \cos \phi = 0.908 \)) and 0.4 kV at \( \cos \phi = 0.9504 \) (initial \( \cos \phi = 0.897 \)) was obtained. In this case, the \( \cos \phi \) on the low side increased, since the generation of reactive power occurs on the section itself.

Let us define the costs of generation and transmission of reactive power using synchronous motors. The costs of generating \( Q \) synchronous motors are determined only by the cost of additional losses of active power in the stator winding and the motor excitation winding caused by the production of \( Q \).

The magnitude of the total losses \( \Delta P_M \) caused by the generation of \( Q \) will be [1]:

\[
\Delta P_M = \frac{D_1}{Q_n} \cdot Q + \frac{D_2}{Q_n^2 \cdot N} \cdot Q ,
\]

where \( D_1, D_2 \) are constant coefficients depending on the technical parameters of synchronous machines [2-4]; \( Q \) is the total reactive power generated by all SM; \( Q_n \) is the nominal capacity of a single SM.

Substituting the values in formula (1), we obtained \( \Delta P_M = 7.78 \text{ kW} \).

The annual cost of electricity losses during the operation of the plant for the production of \( Q \):

\[
C = C_0 \cdot \Delta P_M ,
\]

where \( C_0 \) is the unit cost of power losses, RUB/kW.

The total cost is defined as [1]:

\[
\Omega = E_p \cdot N \cdot K_r + C_0 \cdot \left[ \frac{D_1}{Q_n} \cdot Q + \frac{D_2}{Q_n^2 \cdot N} \cdot Q \right].
\]

where \( E_p \) is the amount of annual deduction, \( E_p = 0.2 \);

\( N \) is the number of synchronous generators, \( N=2 \);

\( K_r \) – the cost of the excitation regulator.

The excitation regulator on the DTS is available, so the cost of its acquisition is absent.

Substituting numerical values in the formula (3), we obtained \( \Omega = 661.3 \text{ rubles} \).

Let us define the cost of generation and transmission reactive power using low-voltage capacitor banks.

The reactive power \( Q \) of the necessary capacitor plant is determined by the formula [1]:

\[
Q = 2 \cdot \pi \cdot f \cdot C \cdot U^2 ,
\]

where \( C \) is the sum of the three phase tanks for the three-phase capacitor.

Substituting the values in formula (4), we obtained “\( Q \)” = 102.5 kVAR.

We choose a low-voltage capacitor bank brand KRM – 0.4–105–7.5 UZ, costing 73400 RUB.

The costs associated with the introduction of compensating funds include the costs of installing new equipment and dismantling obsolete ones. 30% of the value of the LBC is allocated for the installation of new and dismantling of old equipment.

The main share of the estimated costs for the BC is the deductions from the capital investments for its installation. In the value of the BC, it is necessary to distinguish between a constant part that does not depend on the cardinality of the BC and a variable part proportional to its power [1]:

\[
K = K_0 + K_u \cdot Q_H ,
\]

where \( K_0 \) - constant investment; \( K_u \) - unit cost of installation of BC (\( U<1 \text{ kV} \) \( K_u = 12 \text{ thousand RUB/MVAr} \), for \( U>1 \text{ kV} \) \( CU = 6 \text{ thousand RUB/MVAr} \)).

Substituting values in the formula (5), we obtained \( K = 74624 \text{ rubles} \).

The annual cost of electricity losses during operation of the plant for the production of \( Q \):

\[
C = C_0 \cdot \Delta P_{bh} ,
\]
where $\Delta P_{bk}$ – the total value of losses in electrical installations up to 1 kV equals $\Delta P_{bk} = 4.5$ kW/MVAR, for $U=6$-10 kV $\Delta P_{bk} = 2.5$ kW/MVAR.

Substituting values in the formula (6), we obtained $C=39.05$ RUB.

Estimated costs are determined by [1]:

$$\Omega = E \cdot K_0 + \left[ E \cdot K_0 \left( \frac{\dot{U}_{bk}}{U} \right)^2 + C_0 \cdot \Delta P_{bk} \right] \cdot Q,$$

where $E$ is the total annual deductions from capital investments, which for the electrical equipment up to 20 kV is equal to 0.223; $\dot{U}_{bk}$ – the ratio of u N BC to u n network voltage up to 1 kV $\dot{U}_{bk} = 1$, $U = 6$-10 kV $\dot{U}_{bk} = 1.05$.

Substituting the numerical values into formula (7), we obtained $\Omega = 18305.71$ RUB. Capital costs for the acquisition of the LBC brand KPM-0.4-105-7.5 U3 will be based on installation 95420 rubles. The annual costs for servicing the low-voltage capacitor plant are 18305.71 rubles.

Define the costs of generation and transmission of reactive power using high-voltage capacitor batteries.

According to the formula (4), the reactive power $Q$ of the high-voltage capacitor installation is $Q = 3357.28$ kVAR. We choose a high-voltage capacitor bank of the mark UKL (P) 57-6.3-3600 UZ, costing 1575200 rubles (including VAT).

The main share of the estimated costs for the BC is the deductions $K = 1595342$ rubles. The annual cost of electricity losses during the operation of the plant for generating reactive power $C = 713.36$ rubles. Estimated costs amounted to $\Omega = 352120.51$ rubles. Capital costs for the acquisition of the HBC of the mark UKL (P) 57-6.3-3600 U3 will be 2047760 rubles. The annual cost of maintaining a high-voltage capacitor plant is 352120.51 rubles.

Similarly, the reactive power was compensated for the II section. In the absence of reactive power compensation, $\cos \varphi$ is measured on the high and low side. The values of $\cos \varphi$ turned out to be equal to:

- on the side $6 - \cos \varphi = 0.568$;
- $0.4 - \cos \varphi = 0.8944$.

The measurements of $\cos \varphi$ in the overexcitation of synchronous machines produced the following results:

- on the side of 6 kV the resulting $\cos \varphi = 0.62$ (initial $\cos \varphi = 0.568$);
- on the side of 0.4 kV the resulting $\cos \varphi = 0.8944$ (initial $\cos \varphi = 0.8944$).

The values after the installation of the IBD:

- on the side of 6 kV the resulting $\cos \varphi = 0.978$ (initial $\cos \varphi = 0.568$);
- on the side of 0.4 kV the resulting $\cos \varphi = 0.8944$ (initial $\cos \varphi = 0.8944$).

Values of $\cos \varphi$ after the NBK installation:

- on the side of 6 kV the resulting $\cos \varphi = 0.5787$ (initial $\cos \varphi = 0.568$);
- on the side of 0.4 kV the resulting $\cos \varphi = 0.9498$ (initial $\cos \varphi = 0.8944$).

HBC mark UKL (P)57–6.3–3600UZ was chosen. The cost of installation will be 2 047 760 rubles. The annual cost of maintaining a high-voltage condenser plant is 352 120.51 rubles. The capital costs for the acquisition of the LBC brand KRM-0.4-105-7.5 U3 will be 95 420 rubles. The annual costs for servicing the low-voltage capacitor plant are 18 305.71 rubles. The cost of reactive power compensation using a synchronous engine will amount to 676 rubles.

4. Conclusion

1) To compensate the reactive power on the high side, a smaller capacitance of the capacitor bank is required. So, according to the second section, the HBC capacity was 99 μF, and the LBC’s capacity was 680 μF.

2) The capacitance of capacitor banks can be selected in such a way that reactive power is sufficient for consumers on both the low and high sides.
3) On the basis of the technical and economic analysis at the RTP-41 gas-chemical plant, it is expedient to carry out the generation of reactive power using synchronous motors operating in a generator mode with overexcitation.

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