Minimization of active capacity losses in cable power lines of 0.4 kV using optimally distributed compensating devices at petrochemical and oil refining enterprises

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Abstract. We propose a solution for optimization problem of minimizing active power losses for radial power supply scheme by optimal distribution of a given amount of reactive power between the compensating devices. We considered a single-line power supply scheme for a group of pumps of technological installation at a chemical plant. A mathematical model of the optimization problem is compiled by the criterion of active losses minimum in power lines depending on the reactive power flow. We obtained the distribution of optimal values of reactive power between the compensating devices of asynchronous motors for the specified \( \tan \phi \). Quantitative and cost estimations are given for reducing the active power losses in power transmission lines when using capacitor plants, the reactive power of which is optimally distributed. We investigated the influence of starting currents on a circuit when asynchronous motor and capacitor installation are simultaneously turned on. We established the absence of an additional dynamic load on the supply lines.

Introduction

Large petrochemical and oil refinery enterprises are classified as hazardous industries, they are attributed to the 1st category of power supply reliability and provide electricity for their production using the radial power supply schemes [1-5]. In this case, the power lines are of considerable length due to the geographical size of the enterprise. Petrochemical enterprises and oil refineries have a huge number of consumers, i.e. asynchronous motors of 0.4 kV voltage of low and medium power. Copper and aluminum cables of small cross sections (with high active resistances) are used to power them. Calculations of energy losses in such lines show significant values. These circumstances determine the search for a solution to the problem of reducing active power losses in 0.4 kV power lines [6,7].

Nowadays, petrochemical enterprises do not use capacitor units connected directly to a source of reactive power, despite the fact that they were present in the original design documentation. Reactive power compensation devices are installed in the shop transformer substations at the 0.4 kV side, thereby unloading power transformers and higher 6/10 kV transmission lines. At the same time, the 0.4 kV lines supplying electrical installations remain loaded by excess reactive power. Electrical engineers of these enterprises explain their choice by the following reasons:

- The low cost of electricity and the cost of active power losses in 0.4 kV lines do not have a great impact on the cost of products;
- Due to the massive introduction of frequency converters to asynchronous motors, the capacitor units needed to be replaced with more modern ones, which required additional capital investments.


However, the growth of electricity tariffs forced specialists in the field of electricity supply to look for ways to reduce the cost of products. Consequently, the issues concerning reducing active power losses at petrochemical enterprises and oil refineries have become very urgent [8-11]. Among the other things, the engineers returned to the idea of using reactive power compensation devices directly at the sources, namely, asynchronous motors, thereby unloading the 0.4 kV supply lines. In addition, there appeared the task of developing a technical solution for connecting a compensation device directly to an induction motor.

Materials and methods

The following scientific problem is posed: minimizing of active power losses in power lines of 0.4 kV of a radial power supply scheme by solving an optimization problem of optimal distribution of reactive power of compensating devices between a given number of induction motors. The objective function of active power losses (1) is a nonlinear function, therefore, the problem is nonlinear and it is solved using the Lagrange multipliers method.

The losses of active power during transmission of electricity to the consumer is determined by the expression:

$$\Delta P = \frac{P^2 + Q^2}{U^2} R$$

where $P$ is active power in line, W; $Q$ is reactive power in line, Var; $U$ is line supply voltage, V; $R$ is resistance of power line, Ohm.

When a consumer installs a compensation device ($Q \neq 0$), these losses are reduced to

$$\Delta P = \frac{P^2 + (Q - Q_c)^2}{U^2} R.$$  

Thus, reactive power compensation allows one to reduce active power losses in power supply circuit and, consequently, to improve the technical and economic performance of this circuit. From expressions (1), (2) it can be seen that power losses $\Delta P$ have two components: the losses from flowing through the active power line $P$ and the losses from flowing through the line of reactive power $Q$, i.e. $(Q - Q_c)$. Since the compensation of reactive power affects only the second component of losses, further we will consider the losses of active power only from the flow through the lines of reactive power. For the power supply system, the total power of the compensating devices $Q_c$ may be specified by specific technical conditions. In this case, the specified power $Q_c$ is required to be optimally distributed within the power supply system. This is a conditional optimization problem, which can be solved by the Lagrange method [12, 13].

We consider a problem of conditional optimization for the radial scheme of power supply of a group of pumps at a technological installation for producing a liquefied chemical product at a petrochemical plant. Asynchronous motors $M_1$, $M_2$, $M_3$, $M_4$, $M_5$, which consume reactive power $Q_1$, $Q_2$, $Q_3$, $Q_4$, $Q_5$, are powered by 0.4 kV cable lines from a distribution point with a supply voltage $U = 380$ V. Active resistances of lines between the source and consumers are $R_1$, $R_2$, $R_3$, $R_4$, $R_5$. Technical characteristics of motors, cables, magnetic starters and circuit breakers are shown in Figure 1. It is technically possible to install a compensation device of $Q_c$ power for each asynchronous motor.

Further we find the optimal distribution between five asynchronous motors of a given total power of compensating devices $Q_c$, which corresponds to $\tan \varphi = 0.35$ for RP-1 buses. We use the optimality criterion, i.e. the minimum losses of active power from the flow of reactive power in power supply circuit of a group of pumps of a technological installation.

The target function to be minimized, which represents the active power losses in the circuit, has the form:
$$\Delta P = \left( Q_1 - Q_{c1} \right)^2 \frac{R_1}{U^2} + \left( Q_2 - Q_{c2} \right)^2 \frac{R_2}{U^2} + \left( Q_3 - Q_{c3} \right)^2 \frac{R_3}{U^2} + \left( Q_4 - Q_{c4} \right)^2 \frac{R_4}{U^2} + \left( Q_5 - Q_{c5} \right)^2 \frac{R_5}{U^2} \rightarrow \min.$$  

The relative minimum of the target function is found taking into account the following limitation:

$$Q_{c1} + Q_{c2} + Q_{c3} + Q_{c4} + Q_{c5} - Q_c = 0.$$  

The Lagrange function is:

$$L = \frac{1}{U^2} \left[ \left( Q_1 - Q_{c1} \right)^2 R_1 + \left( Q_2 - Q_{c2} \right)^2 R_2 + \left( Q_3 - Q_{c3} \right)^2 R_3 + \left( Q_4 - Q_{c4} \right)^2 R_4 \right] + \lambda \left( Q_{c1} + Q_{c2} + Q_{c3} + Q_{c4} + Q_{c5} - Q_c \right) \rightarrow \min.$$  

In order to find the minimum of function $L$, we calculate its partial derivatives and equate them to zero:
y meters, the required power can be obtained from the measurement of contact connections and the resistance of the cable active resistance should be determined taking into account the number of phases and the area from the engine to the distribution point buses should be taken into account. This means that the electrical installation is equipped with incomplete loading, so it is necessary to determine the active and reactive powers of the asynchronous motor, taking into account the load factor. In case the electrical installation is equipped with compensating devices, several factors should be taken into account in a mathematical model. As a rule, at petrochemical enterprises and oil refineries asynchronous motors operate in continuous mode for RP-1 buses are given in technical characteristics of asynchronous motors.

We solve the resulting system of linear equations (3), determine the optimal values of reactive powers of the compensating devices \( Qc1, Qc2, Qc3, Qc4, Qc5 \) and find the minimum for active losses \( \Delta P \) from flowing along the lines of reactive power.

Analysis of results of solving the optimization problem shows that the optimal distribution of a given total reactive power on the buses of the distribution point \( Qc \) for the radial power supply scheme under consideration is equal to:

\[
(Q_1 - Q_{c1})R_1 = (Q_2 - Q_{c2})R_2 = (Q_3 - Q_{c3})R_3 = (Q_4 - Q_{c4})R_4 = (Q_5 - Q_{c5})R_5.
\]

When solving the problem of optimal distribution of a given total reactive power between compensating devices, several factors should be taken into account in a mathematical model. As a rule, at petrochemical enterprises and oil refineries asynchronous motors operate in continuous mode with incomplete loading, so it is necessary to determine the active and reactive powers of the asynchronous motor, taking into account the load factor. In case the electrical installation is equipped with active and reactive energy meters, the required power can be obtained from the measurement results. The object under study lacked electricity metering devices, therefore, based on the measured values of motor currents, as well as using the method given in [14], the actual values of active and reactive power of asynchronous motors were determined taking into account the load factor (Table 1).

### Table 1. Technical characteristics of asynchronous motors.

| №  | Type  | \( I_1, A \) | \( K_r \) | \( P_e, kW \) | \( \text{tg} \varphi \) | \( Q_s, \text{kVar} \) | \( Q_{opt}, \text{kVar} \) |
|----|-------|-------------|----------|--------------|-----------------|-----------------|-----------------|
| 1  | 4A200M4 | 68          | 0.65     | 26.1         | 0.74            | 19.3            | 14.4            |
| 2  | 4A200L4 | 83          | 0.72     | 35.2         | 0.70            | 24.7            | 18.5            |
| 3  | 4A225M4 | 99          | 0.68     | 40.2         | 0.70            | 28.3            | 21.4            |
| 4  | 4A200L4 | 83          | 0.63     | 30.8         | 0.73            | 22.6            | 16.5            |
| 5  | AO 93-4 | 130         | 0.6      | 47.9         | 0.87            | 41.7            | 6.4             |

When determining the active resistances \( R_i \), all components of the three-phase transmission line in the area from the engine to the distribution point buses should be taken into account. This means that the cable active resistance should be determined taking into account the number of phases and the ambient temperature, as well as the contact resistances of contact connections and the resistance of detachable contacts of magnetic starters and automatic switches [15].

The values of the optimally distributed reactive power between the compensating devices of asynchronous motors of the technological installation providing \( \text{tg} \varphi = 0.35 \) for RP-1 buses are given in Table 1.
When developing the electrical circuit for connecting a capacitor unit to an asynchronous motor, we considered a preliminary version of their alternate operation, i.e. firstly the engine was turned on, then a capacitor unit was automatically connected using a time relay. In order to simplify the developed scheme, we investigated the possibility of simultaneous connection to the circuit of an induction motor and a capacitor unit, the reactive power of which is determined by the criterion of minimum losses. The study was carried out using a virtual research unit assembled in Matlab 2010. We analyzed the impact of starting currents of asynchronous motor and the device for reactive power compensation when they were simultaneously connected to the circuit on the supply cable line of 0.4 kV. The scheme of simulation is shown in Figure 2. We calculated parameters of the equivalent circuit for each asynchronous motor of the technological installation. The load on the motor shaft was set taking into account the adopted load factor, the reactive power of the condenser unit was took according to the results of solving the optimization problem.

Results
Active losses in the 0.4 kV transmission lines of the considered technological installation resulted from the flow of reactive power without compensating devices are 9067 W. When a compensation device with optimum reactive power is installed for each asynchronous motor, the active losses from the flow of reactive power will decrease up to 1970 W. In general, the reduction of costs for the transfer of active power to engines when installing compensating devices to them amounted to 7097 W. The energy savings for a tariff of 3.38 rubles/kWh amounted to 211385 rubles/year. The cost of condenser units and additional equipment according to the proposed technical solution is 161,659 rubles. Thus, by saving energy, the project can be recouped in 1 year, which is acceptable for petrochemical and refining industries.

The results of simulating the processes of simultaneous activation of asynchronous motor and condenser unit show that the resulting input current is slightly reduced, which indicates that there is no additional dynamic load on the power lines, so it is proposed to use the wiring diagram shown in Figure 3.
Figure 3. Electrical wiring diagram of an asynchronous motor and reactive power compensation device: QF is circuit breaker; KK1 is thermal relay; KM1 is magnetic starter; FU is for fuse; SB-2 is “Stop” button; SB-1 is “Start” button.

The practical significance of this research is to minimize active power losses from reactive power flow. This results in minimization of active losses in 0.4 kV lines, power transformers and higher power lines in general, as well as in development of a technical solution for the proposed measure. Our future work will be aimed at development of algorithms for optimal control of capacitor installations in real time with varying loads of electrical installations.

Conclusions
1. A mathematical model is proposed for the optimization problem by the criterion of active losses minimum in power lines from reactive power flow for a radial power supply using the example of a power supply for a group of pumps of a chemical plant.
2. The optimal distribution of reactive power between the compensating devices of asynchronous motors was determined.
3. A quantitative assessment is given for reducing active power losses in power lines when using capacitor units, the reactive power of which is optimally distributed.
4. A feasibility study of the design solution was carried out; the project payback period is acceptable for making a decision on the implementation of the proposed project at petrochemical and oil refining enterprises.
5. An electrical circuit diagram has been developed for connecting a capacitor unit to an asynchronous motor, taking into account the study of inrush currents while simultaneously turning them on.
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