Optimization model of power supply system of industrial enterprise

V Panteleev, S Zilberman, G Pilyugin, R Petukhov, E Sizganova and M Mashukov

Siberian Federal University 79 Svobodny, Krasnoyarsk, 660041, Russia

E-mail: pvi0808@rambler.ru

Abstract. In this paper, the problem of optimizing the generated reactive power distribution for reducing the loss of active power in the elements of industry power supply system presented. The problem of optimal distribution of generated reactive powers by synchronous motors in the power supply systems belongs to the nonlinear mathematical programming class and can be solved by using the Lagrange multiplier method. The Lagrange method allows one to reduce the problem of conditional optimization (that is, finding the relative extremum of the objective function with certain limitations) to the simpler problem of unconditional optimization (the search of an absolute extremum).A complete mathematical model of optimization problem of the rational distribution of the generated reactive power by the synchronous motors in order to reduce the loss of active power in the power supply system elements of an industrial enterprise developed. The obtained mathematical problem allows one to consider a number of limitations related to both the mode of operation for the individual power supply system elements and the entire system as it is.

As of today, energy saving and improving the energy efficiency of electric power systems, which includes the power supply systems for industrial enterprises, are considered to be global techno-economic tasks. According to the order of the Government of the Russian Federation No. 1715-r dated November 13, 2009, one of the top priority directions in the measures implementations, covered in the "Energy Strategy of Russia for the period until 2030" is the "improvement of energyperformance and economic efficiency of the Russian economy and power production, inter alia through structural changes and activation of technological energy saving".

The compensation for reactive power is one of the potential methods of energy saving, the result of which is to reduce the loss of active power in the electrical grid, to increase the capacity of its elements, and to improve the voltage quality in the network nodes. The compensation may be performed by means of using various devices. These include static capacitor batteries, synchronous compensators, series capacity devices, shunt reactors, static reactive power compensators, etc. The most widely used in the industry are synchronous motors, which are able to generate reactive power at the nodes of electrical power consumption. Synchronous motors are used as drives for hammer grinders and ball mills of mining facilities, main pumps of oil pumping stations, continuous mills in metallurgy, etc. [1, 2, 3].

In view of the foregoing, one can make a conclusion that the problem of optimal distribution of generated reactive powers by synchronous motors in power supply systems is significant and relevant. Such a problem belongs to the nonlinear mathematical programming class and can be solved by using the Lagrange multiplier method. [4, 5].

The Lagrange method allows one to reduce the problem of conditional optimization (that is, finding the relative extremum of the objective function with certain limitations) to the simpler problem of unconditional optimization (the search of an absolute extremum) [4]. Additionally, the analysis shows [6] that, compared to the gradient methods of nonlinear optimization, Lagrange multiplier method meets the requirements of precision, completeness, and convenience of realization for solving the problem.

We shall analyze in short form the power supply system of an industrial enterprise, which includes the following elements: the power transformer (T) of the main step-down substation (MSDS), the cable power lines (W), the synchronous motors (MS), and the generalized load (N) shown in figure 1.
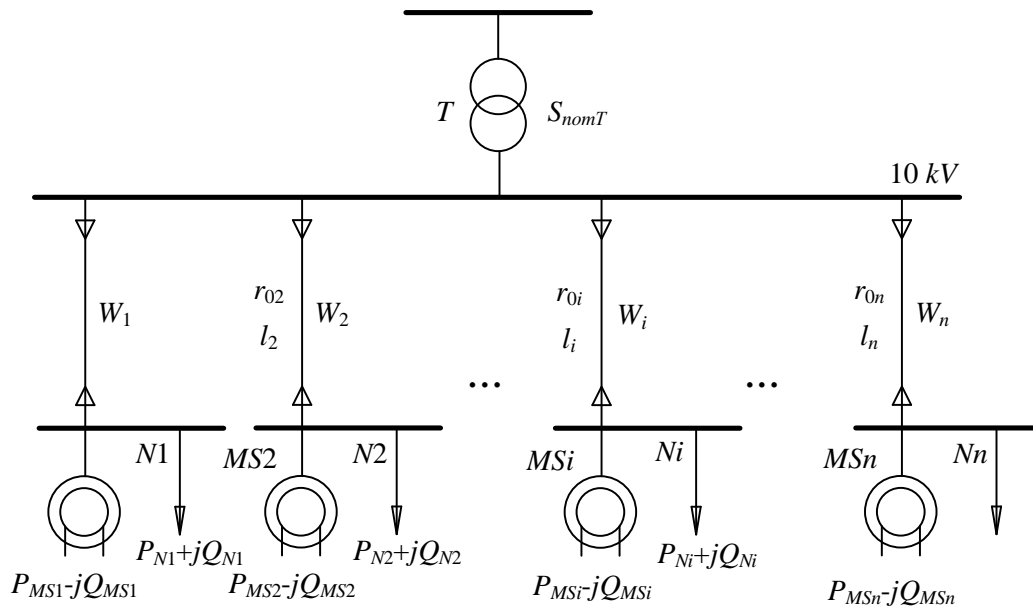

Figure 1. Distribution network of an industrial enterprise.

As the optimization criterion characterizing the transmission efficiency and the power consumption in the industrial network at hand, we will take the minimum of the total active power losses in the power supply system elements, kW,

$$\Delta P \to \min$$

We will formulate an optimization model of the power supply system based on the objective function of the total active power losses while taking into account the limitations caused by certain technological conditions of the enterprise's distribution network operation:

$$\Delta P = \Delta P_T^{MSDS} + \Delta P_W + \Delta P_{MS}^{staW} + \Delta P_{MS}^{RPL}.$$

Active power losses in the power transformer MSDS, kW[7],

$$\Delta P_T^{MSDS} = \Delta P_{NL} + \frac{\Delta P_{LLF}}{S_{nomT}^2} \cdot \left(\sum_{i=1}^{n} (P_{Ni} + P_{MSi})^2 + \sum_{i=1}^{n} (Q_{Ni} - Q_{MSi})^2 \right)$$

where ΔP_{NL} – idling losses of the power transformer, kW; ΔP_{LLF} – short-circuit losses of the power transformer, kW; P_{Ni} and Q_{Ni} – active and reactive powers of the generalized load, kW and kV respectively; P_{MSi} and Q_{MSi} – consumed active and generated reactive powers of the synchronous motor, kW and kV respectively; S_{nomT} – rated full capacity of the power transformer, kV·A.

Cable power line losses, kW [7],

$$\Delta P_W = \frac{1}{U_{nom}^2} \cdot \sum_{i=1}^{n} \left((P_{Ni} + P_{MSi})^2 + (Q_{Ni} - Q_{MSi})^2 \right) \cdot r_{0i} \cdot l_i$$

here U_{nom} – rated voltage of the industrial enterprise distribution network, kW; r_{0i} – linear resistance of the cable line, Ohm/km; l_i – cable line length, km.

Stator winding losses of the synchronous motor, kW [8],

$$\Delta P_{MS}^{staW} = 3 \cdot \sum_{i=1}^{n} r_{pi} \cdot I_{pi}^2 = \frac{1}{3 \cdot U_p^2} \cdot \sum_{i=1}^{n} r_{pi} \cdot \left(P_{MSi}^2 + Q_{MSi}^2 \right)$$

here r_{pi} – phase resistance of the synchronous motor stator winding, Ohm; I_{pi} and U_p – phase current and stator winding voltage of the synchronous motor, A and kV respectively.

Losses in the synchronous motor, caused by the reactive power output, kW [9],

$$\Delta P_{MS}^{RPL} = \sum_{i=1}^{n} \frac{D_{1i} \cdot Q_{MSi}}{Q_{MSnomi}} + \sum_{i=1}^{n} \frac{D_{2i} \cdot Q_{MSi}^2}{Q_{MSnomi}^2}$$

here Q_{MSnomi} – rated reactive power of the synchronous motor, kVAr; D_{1i} and D_{2i} – computed values, contingent upon the properties of a particular motor, kW.

Since the compensation of reactive power cannot affect the active-power flow in any way, we exclude the *relevant* parts when forming the equation for the objective function. In addition, we exclude from the calculation the conditional-constant idling losses of the MSDS power transformer ΔP_{NL}. Thus, the objective function of overall losses of active power, kW,

$$\Delta P = \frac{\Delta P_{LLF}}{S_{nomT}^2} \cdot \sum_{i=1}^{n} (Q_{Ni} - Q_{MSi})^2 + \frac{1}{U_{nom}^2} \cdot \sum_{i=1}^{n} (Q_{Ni} - Q_{MSi})^2 \cdot r_{0i} \cdot l_i$$

$$+ \frac{1}{3 \cdot U_p^2} \cdot \sum_{i=1}^{n} r_{pi} \cdot Q_{MSi}^2 + \sum_{i=1}^{n} \frac{D_{1i} \cdot Q_{MSi}}{Q_{MSnomi}} + \sum_{i=1}^{n} \frac{D_{2i} \cdot Q_{MSi}^2}{Q_{MSnomi}^2} \rightarrow \min$$

For completeness of the optimization model, we apply a number of limitations to the objective function:

1. By the value of the power factor for the electric receivers connected to the distribution network of an industrial enterprise

$$\sum_{i=1}^{n} (Q_{Ni} - Q_{MSi}) = \tan \varphi_n \cdot \sum_{i=1}^{n} (P_{Ni} + P_{MSi}),$$

where$\tan \varphi_n$ – power factor.

2. By the reactive power value generated by the synchronous motor in the specific node on the power supply system [10]

$$Q_{MSi}^{\min} \leq Q_{MSi} \leq Q_{MSi}^{\max},$$

where $Q_{MSi}^{\min}$ and $Q_{MSi}^{\max}$ – the lower and upper limits of the development of the reactive power by the motor respectively, kVAr.

3. By the voltage in the nodes of the electrical power supply system, is determined according to the interstate standard [11].

$$U_i^{\min} \leq U_i \leq U_i^{\max},$$

where $U_i^{\min}$ and $U_i^{\max}$ – lower and upper limits of the voltage magnitude in the i-node, kW.

Thus, a complete mathematical model of optimization problem of the rational distribution of the generated reactive power by the synchronous motors in order to reduce the loss of active power in the power supply system elements of an industrial enterprise developed.

The obtained mathematical problem allows one to consider a number of limitations related to both the mode of operation for the individual power supply system elements and the entire system as it is.

References
[1]   Efimovskii A V and Vladimirov Yu V 2010 Expediency of using a synchronous motor as a reactive power compensator *Bulletin of the National Technical University "KhPI* (Kharkiv: NTU"KhPI") **45** pp 88-94

[2]   Veselov A E, Karpov A S and Yaroshevich V V 2009 *Technical and economical evaluation of engaging efficiency of synchronous electric motors of enterprises to reactive power production* (Bulletin of the Bauman MSTU) **12(1)** pp 83-8

[3]   Zamyatin E O, Shklyarskiy Y E and Yakovleva E V 2016 Concept for electric power quality indicators evaluation and monitoring stationary intellectual system development *Int. Journal of applied engineering research* **11(6)** pp 4270-4

[4]   Kostin V N 2003 *Optimization problems of electrical energy industry* (St. Petersburg: NWOTU)

[5]   Poliakov V N and Schreiner R T 2017 *Power-efficient motor modes in alternating current systems* (Yekaterinburg: UrFU)

[6]   Bandi B *Metodyoptimizatsii. Vvodnyikurs* (Moscow: Radio isviaz)

[7]   Barybin Yu G   *et al* 1990 *Reference book on designing of electric power supply* (Moscow:Energoatomizdat)

[8]   Voldek A I 1978 *Electrical machines* (Leningrad:Energia)

[9]   Fedorov A A *Reference book of electric power supply and electrical machineries* (Moscow: Energoizdat)

[10]   Palamarchuk S I 1993 Determination of available reactive power of generating buses *Elektrichestvo* **11** 9-14

[11]   GOST 32144-2013 *Electromagnetic compatibility of technical equipment. Quality standard of electric energy in general-purpose power supply systems* (Moscow: Standartinform)