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IMPROVING THE EFFICIENCY OF 6–10 KV POWER GRIDS OF INDUSTRIAL ENTERPRISES THROUGH OPTIMAL REACTIVE POWER CONTROL

The article deals with improving the efficiency of an industrial power system, which is determined by the level of power losses in its elements.

One of the most important methods of increasing the efficiency of power supply systems and distribution networks that ensure the transmission and distribution of electricity is to reduce the amount of electrical energy that is expended in this process. Reducing power losses in electrical grids is achieved by reducing the reactive component of the electric current, i.e., by increasing the cos φ. The Electrical Installation Code recommends, first of all, using the synchronous motors available at the enterprise.

It is reasonable to solve the problem of minimizing active power losses in the power grid using the method of mathematical modeling and mathematical programming.

The article presents the main features of the criterion programming method for solving a class of problems with a positive degree of difficulty, which is quite well-known in the electric power industry for solving optimization problems.

We propose the method of criterion programming to solve the problem of improving the efficiency of the power grid by optimal control of the operation of synchronous motors according to the reactive power mode.

Keywords: Electrical network, reactive power, minimization of active power losses, synchronous motors, criterion programming.

Introduction

The efficiency of the power supply system is determined by the level of power losses in its elements.

One of the most important methods of increasing the efficiency of power supply systems and distribution networks that ensure the transmission and distribution of electricity is to reduce the amount of electrical energy that is expended in this process. According to international experts, the relative losses of electric power during transmission and distribution in power grids in most countries can be considered satisfactory if they do not exceed 4-5%. Losses at the level of 10% can be considered the maximum allowable as regards the physics of transmission through power grids.

Thus, one of the criteria for evaluating the efficiency of electrical grids and systems is the levels of power losses in them.

Materials and methods

Power losses in lines

Transmitting a significant amount of reactive power through lines and transformers on the power grid is unprofitable for the following main reasons:

(a) there are additional losses of active power and energy in all elements of the power supply system due to their reactive power load;

(b) there are additional voltage losses;

(c) loading transmission lines and transformers of the power supply network with reactive power reduces the capacity of the network, which in some cases does not allow using of the full generators of power plants.

The power-factor correction is used to eliminate the above causes that reduce the efficiency of power supply networks. It can be increased both without the use of compensating devices and with the use of compensating devices.

Use of mathematical programming methods

It is reasonable to solve the problem using mathematical programming methods. One of the methods is the method of criterion programming.

The principal task of this method is formulated as follows:

- to find the minimum value of the function

$$Y(X),\ X = (X1,\ X2,\ \ldots,\ Xm), \tag{1}$$

- provided $X1 > 0, X2 > 0, \ldots, Xm > 0,$

- and constraints

$$g_1(X) \le 1,\ g_2(X) \le 1,\ \ldots,\ g_p(X) \le 1.$$

It is assumed that the objective function *Y(X)* and the constraints g*(X)* are expressed by positive generalized polynomials in the form of

$$Y(X) = \sum_{i=1}^{n} A_i \prod_{j=1}^{m} X_j^{a_{ij}}\ , \tag{2}$$

where $A_i > 0$, α_{ij} are arbitrary real numbers;

X_j is an optimized variable;

n is the number of terms in the objective function and constraints;

m is the number of optimized variables;

α_{ij} is any real number.

To determine the minimum of the objective function in criterion programming (a class of problems with non-zero degree of difficulty) the duality theory is applied [5, 6], where the direct problem of searching for optimal values X_0 is replaced by the determination of components of the vector of similarity criteria π_0 with subsequent identification of the maximum of such multiplicative function $D(\pi)$, that

$$D_{\max}(\pi_0) = Y_{\min}(X_0).$$

In this case, the function $D(\pi)$ is called dual, and the determination of its maximum value and the maximizing vector π_0 is called the solution of the dual problem, respectively.

For the objective function $Y(X)$ and constraints $g(X)$ of a direct problem with a positive degree of difficulty $(d = n - m - 1 > 0)$, which is most typical for technical and economic optimization problems set in power engineering, the general solution for dual constraints will have the form of [4]:

$$\pi = b_0 + \sum_{j=1}^{d} c_j b_j, \tag{3}$$

where c_j is the j-th basis variable; it has a value of an arbitrary real number satisfying the non-negativity constraint:

$$b_{i0} + \sum_{j=1}^{d} c_i b_{ij} \geq 0 \qquad i = 1, 2, 3, \ldots n;$$

where b_0 is the normalization vector, b_{i0} is its i-th component; b_j is the j-th residual vector, b_{ij} is its i-th component.

By substituting expression (3) into the solution of the dual problem and after some transformations, we obtain the expression of the maximizing vector $\pi 0$ through the generalized constants of the objective function and the constraints:

$$\prod_{i=1}^{n} \pi_i^{b_{ij}} = \prod_{i=1}^{n} A_i^{b_{ij}} \quad . \tag{4}$$

When determining the optimal values of the variables of the direct criterion programming [4, 9] problem we proceed from the fact that

$$D(\pi_0)_{\max} = \prod_{i=1}^{n_1} \left(\frac{A_i}{\pi_i} \right)^{\pi_i} \cdot \prod_{k=1}^{p} \left(\lambda_k \right)^{\pi_k}, \tag{5}$$

$$Y_{\min}(X_0) = D_{\max}(\pi_0) = \sum_{i=1}^{n} A_i \prod_{j=1}^{m} X_{j0}^{a_{ji}}, \tag{6}$$

where X_0 is the desired minimizing vector of the main problem;

n_1 is the number of terms of the objective function;

p is the number of constraints;

λ_k is the k-th constraint.

Based on the definitions of the similarity criteria π we can write n equations in the form of

$$D_{\max}(\pi_0)\pi_{i0} = A_i \prod_{j=1}^{m} X_{j0}^{a_{ji}}, \tag{7}$$

where $i = 1, 2, 3, \ldots, n$.

Logarithmizing the system of equations (7) defines a system of linear equations with respect to InX_{j0}:

$$\ln = \left(\frac{D_{\max}(\pi_0)\pi_{i0}}{A_i} \right) = \sum_{j=1}^{m} \alpha_{ji} \ln X_{j0}, \tag{8}$$

where $j = 1, 2, 3, \ldots, m$.

In this system of equations, the $(d + 1)$ equations are linearly dependent. By isolating a system of m linearly independent equations from (8) and solving it, we find a vector of solutions with respect to InX_{j0}:

$$B = \begin{vmatrix} \ln B_1 \\ \ln B_2 \\ \ldots \\ \ln B_m \end{vmatrix} = \begin{vmatrix} \ln X_{10} \\ \ln X_{20} \\ \ldots \\ \ln X_{m0} \end{vmatrix}. \tag{9}$$

Exponentiating the obtained solution determines the coordinates of the minimizing point of the main optimization problem, i.e. $X_{10}, X_{20}, X_{30}, \dots , X_{m0}$.

Problem solving algorithm

Theoretical provisions of criterion programming are fully enough described in [3, 4, 5, 6, 7, 8, 9, 10], so we will focus on the algorithm for solving the problem set below.

Figure 1 shows the main section of the 6–10 kV distribution network. Switchgear No.4, No.5, and No.6 are connected to the trunk mains. Synchronous motors, as well as other loads, are connected to the switchgears.

The task is formulated as follows: to optimize the reactive power mode of the electric network. The optimality criterion is a minimum of active power losses on a distribution network section.

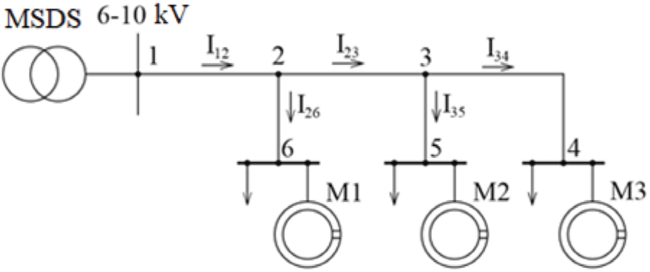

Figure 1 – Diagram of the distribution network section

The mathematical model of the electric grid will have the form of:

$$\Delta P=\sum_{i=1}^{n}3\cdot r_i\cdot\left(I_{ia}^2+I_{ip}^2\right),$$

when

$$I_{ia}\ge G_{ia},\quad I_{ip}\ge G_{ip},$$

where r_i is the active ratio of the *i*-th arms of the electrical network;

I_{ia}, I_{ip} are active and reactive components of the current in the *i*-th arm, respectively;

G_{ia}, G_{ir} are active and reactive current components of the *i*-th arm, respectively, determined by the calculation scheme;

n is the number of arms in the electrical network.

As we can see from the mathematical model, [4, 9] active power losses in the electric network consist of two components: the first depends on active power, and the second – on reactive power. Thus, the task of minimizing the losses of active power has been reduced to determining the optimal values of reactive power, which can be done at the expense of synchronous motors.

Results and discussion

The mathematical model for this problem is written in the form of

$$\Delta P_p = 3 \cdot r_{12} \cdot I_{12p}^2 + 3 \cdot r_{23} \cdot I_{23p}^2 + 3 \cdot r_{34} \cdot I_{34p}^2 + 3 \cdot r_{35} \cdot I_{35p}^2 + 3 \cdot r_{26} \cdot I_{26p}^2,$$

with constraints:

$$I_{12p}^{-1} \cdot G_{12p} \le 1; \quad I_{23p}^{-1} \cdot G_{23p} \le 1; \quad I_{34p}^{-1} \cdot G_{34p} \le 1; \quad I_{35p}^{-1} \cdot G_{35p} \le 1;$$

$$I_{26p}^{-1} \cdot G_{26p} \le 1.$$

The independent variables in this problem are currents in network arms, their number is five, and the total number of terms, including constraints, is 10. The degree of difficulty of the problem *d* [4] will be equal:

$$d = 10 - 5 - 1 = 4.$$

This model with constraints corresponds to the matrix (matrix of power indices at the objective variables) [3,4, 9]:

$$\alpha = \begin{vmatrix} 2 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 \\ 0 & 2 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 2 & 0 & 0 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 2 & 0 & 0 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 & 2 & 0 & 0 & 0 & 0 & -1 \end{vmatrix} \tag{10}$$

Modified by the Gauss-Jordan method, it will have the form of

$$\alpha' = \begin{vmatrix} 1 & 0 & 0 & 0 & 0 & -1/2 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & -1/2 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & -1/2 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & -1/2 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & -1/2 \end{vmatrix} \qquad (11)$$

By taking the reciprocal matrix lying to the right of the unit matrix and adding the unit matrix of size [$(d+1) \times (d+1)$] below, we obtain the matrix β

$$\beta = \begin{vmatrix} 1/2 & 0 & 0 & 0 & 0 \\ 0 & 1/2 & 0 & 0 & 0 \\ 0 & 0 & 1/2 & 0 & 0 \\ 0 & 0 & 0 & 1/2 & 0 \\ 0 & 0 & 0 & 0 & 1/2 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{vmatrix} \qquad (12)$$

The normalization vectors b_0 and the residuals b_j are determined by the known relations from the matrix β. To obtain the normalization vector, take any column vector of the matrix and divide it by the sum of its first components. To obtain the jth residual vector, take the remaining column vector of the matrix β and subtract from it the product of the sum of its first components by the normalization vector. We obtain:

$$b_0 = \begin{vmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 2 \\ 0 \\ 0 \\ 0 \\ 0 \end{vmatrix}; \quad b_1 = \begin{vmatrix} -1/2 \\ 1/2 \\ 0 \\ 0 \\ 0 \\ -1 \\ 1 \\ 0 \\ 0 \\ 0 \end{vmatrix}; \quad b_2 = \begin{vmatrix} -1/2 \\ 0 \\ 1/2 \\ 0 \\ 0 \\ -1 \\ 0 \\ 1 \\ 0 \\ 0 \end{vmatrix}; \quad b_3 = \begin{vmatrix} -1/2 \\ 0 \\ 0 \\ 1/2 \\ 0 \\ -1 \\ 0 \\ 0 \\ 1 \\ 0 \end{vmatrix}; \quad b_4 = \begin{vmatrix} -1/2 \\ 0 \\ 0 \\ 0 \\ 1/2 \\ -1 \\ 0 \\ 0 \\ 0 \\ 1 \end{vmatrix}. \qquad (13)$$

According to (3) the vector of similarity criteria in the general case is written as

$$\pi = \begin{vmatrix} 1 - \frac{1}{2}C_1 - \frac{1}{2}C_2 - \frac{1}{2}C_3 - \frac{1}{2}C_4 \\ \frac{1}{2}C_1 \\ \frac{1}{2}C_2 \\ \frac{1}{2}C_3 \\ \frac{1}{2}C_4 \\ 2 - C_1 - C_2 - C_3 - C_4 \\ C_1 \\ C_2 \\ C_3 \\ C_4 \end{vmatrix}. \qquad (14)$$

Let us define the maximizing vector π. To do this, according to expression (4), write a system of equation

$$\begin{cases}\left(1-\frac{1}{2}C_1-\frac{1}{2}C_2-\frac{1}{2}C_3-\frac{1}{2}C_4\right)^{-\frac{1}{2}}\cdot\left(\frac{1}{2}C_1\right)^{\frac{1}{2}}\cdot\left(2-C_1-C_2-C_3-C_4\right)^{-1}\cdot C_1=\\ =\left(3r_{12}\right)^{-\frac{1}{2}}\cdot\left(3r_{23}\right)^{\frac{1}{2}}\cdot G_{12}^{-1}\cdot G_{23};\\ \left(1-\frac{1}{2}C_1-\frac{1}{2}C_2-\frac{1}{2}C_3-\frac{1}{2}C_4\right)^{-\frac{1}{2}}\cdot\left(\frac{1}{2}C_2\right)^{\frac{1}{2}}\cdot\left(2-C_1-C_2-C_3-C_4\right)^{-1}\cdot C_2=\\ =\left(3r_{12}\right)^{-\frac{1}{2}}\cdot\left(3r_{34}\right)^{\frac{1}{2}}\cdot G_{12}^{-1}\cdot G_{34};\\ \left(1-\frac{1}{2}C_1-\frac{1}{2}C_2-\frac{1}{2}C_3-\frac{1}{2}C_4\right)^{-\frac{1}{2}}\cdot\left(\frac{1}{2}C_3\right)^{\frac{1}{2}}\cdot\left(2-C_1-C_2-C_3-C_4\right)^{-1}\cdot C_3=\\ =\left(3r_{12}\right)^{-\frac{1}{2}}\cdot\left(3r_{35}\right)^{\frac{1}{2}}\cdot G_{12}^{-1}\cdot G_{35};\\ \left(1-\frac{1}{2}C_1-\frac{1}{2}C_2-\frac{1}{2}C_3-\frac{1}{2}C_4\right)^{-\frac{1}{2}}\cdot\left(\frac{1}{2}C_4\right)^{\frac{1}{2}}\cdot\left(2-C_1-C_2-C_3-C_4\right)^{-1}\cdot C_4=\\ =\left(3r_{12}\right)^{-\frac{1}{2}}\cdot\left(3r_{26}\right)^{\frac{1}{2}}\cdot G_{12}^{-1}\cdot G_{26}.\end{cases} \qquad (15)$$

Conclusion

Setting the initial information about the electric network arms and solving the system (15) with respect to the variables C, substituting their values in the expression for the vector of similarity criteria (14), we obtain the numerical values of its components. Further, using expressions (5), (6), (7) (8), and (9), the optimum values of reactive components of currents in the arms of a distribution network are finally determined. Thus, we obtained the solution to the problem of minimizing active power losses in the power grid using the method of mathematical modeling and mathematical programming.

Outcomes

Using the method of criterion programming a model to solve the problem of improving the efficiency of the power grid by optimal control of the operation of synchronous motors according to the reactive power mode has been developed.

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РЕАКТИВТІ ҚУАТТЫ ОҢТАЙЛЫ БАСҚАРУ АРҚЫЛЫ ӨНЕРКӘСІПТІК КӘСІПОРЫНДАРДЫҢ 6–10 кВ ЭЛЕКТР ЖЕЛІЛЕРІНІҢ ТИІМДІЛІГІН АРТТЫРУ

Мақалада оның элементтеріндегі электр энергиясының жоғалу деңгейімен анықталатын өнеркәсіптік кәсіпорынның электрмен жабдықтау жүйесінің тиімділігін арттыру мәселесі қарастырылған.

Электр энергиясын беру мен таратуды қамтамасыз ететін электрмен жабдықтау жүйелері мен тарату желілерінің тиімділігін арттырудың маңызды жолдарының бірі осы процеске жұмсалатын *электр энергиясын тұтынуды азайту болып табылады. Электр желілеріндегі электр энергиясының жоғалуын азайту токтың реактивті құрамдас бөлігін азайту арқылы жүзеге асырылады, яғни. cos φ көбейтіңіз. PUE бұл үшін, ең алдымен, кәсіпорында бар синхронды қозғалтқыштарды пайдалануды ұсынады.*

Математикалық модельдеу және математикалық бағдарламалау әдістерін қолдана отырып, электр желісіндегі белсенді қуат жоғалтуларын азайту мәселесін шешкен жөн.

Мақалада оңтайландыру есептерін шешу үшін электр энергетикасында жақсы белгілі қиындықтың оң дәрежесі бар есептер класын шешуге арналған критериалды бағдарламалау әдісінің негізгі ерекшеліктері берілген.

Реактивті қуат режимі бойынша синхронды қозғалтқыштардың жұмысын оңтайлы басқару есебінен электр желісінің тиімділігін арттыру мәселесін шешу үшін критериалды бағдарламалау әдісін қолдану әдістемесі ұсынылған.

Кілтті сөздер: Электр желісі, Реактивті қуат, Белсенді қуаттың жоғалуын азайту, Синхронды қозғалтқыштар, Критериалды бағдарламалау.

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ПОВЫШЕНИЕ ЭФФЕКТИВНОСТИ ЭЛЕКТРИЧЕСКИХ СЕТЕЙ 6–10 кВ ПРОМЫШЛЕННЫХ ПРЕДПРИЯТИЙ ПУТЁМ ОПТИМАЛЬНОГО УПРАВЛЕНИЯ РЕАКТИВНОЙ МОЩНОСТЬЮ

В статье рассматривается вопрос повышения эффективности системы электроснабжения промышленного предприятия, которая определяется уровнем потерь электрической энергии в её элементах.

Одним из важнейших путей повышения эффективности систем электроснабжения и распределительных сетей, обеспечивающих передачу и распределение электроэнергии, является снижение расхода электрической энергии, который тратится на этот процесс. Снижение потерь электроэнергии в электрических сетях производят за счёт снижения реактивной составляющей электрического тока, *т.е. повышения cos φ. ПУЭ рекомендует для этого в первую очередь использовать имеющиеся на предприятии синхронные двигатели.*

Решить поставленную задачу по минимизации потерь активной мощности в электрической сети целесообразно с использованием методов математического моделирования и математического программирования.

В статье приводятся основные черты метода критериального программирования для решения класса задач с положительной степенью трудности, который достаточно хорошо известен в электроэнергетике для решения оптимизационных задач.

Предлагается методика применения метода критериального программирования для решения задачи повышения эффективности электрической сети за счёт оптимального управления работой синхронных двигателей по режиму реактивной мощности.

Ключевые слова: Электрическая сеть, Реактивная мощность, Минимизация потерь активной мощности, Синхронные двигатели. Критериальное программирование.

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