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Optimizing the Positioning of Power Sources in Industrial Units Electrical Power Systems on the Basis of the Method of Distributed Power Density

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***Abstract*— The article analyzes the electrical power system of a machine construction workshop where optimal positioning of power sources (power substation, distribution points) has to be determined so as to lower the metal consumption. The goal of the work is to develop a model of an efficient electrical power system at an industrial unit employing the method of distributed power density, developed by the authors. This method will help to determine the position of power sources. The amount of energy losses per power transmission and the metal consumption of the system were used as optimization criteria.**

The suggested method is based on the presentation of each surface load in the form of solids of revolution, limited by planes produced by the multiple of the basic function and the load power. The results were analyzed by means of substituting the group of consumers by an equivalent consumer and determining the radius of diffusion.

The method of distributed power density allows to design the system of power supply with better characteristics in terms of minimal losses per power transmission and minimal metal consumption. The suggested method can be used in designing the power systems of industrial units and larger geographical areas. This method will help to determine the best position for reactive power compensators, the installation of which will help to minimize the losses in the system, increase the quality of the power supplied to the consumer unit.

Keywords—electrical power supply, substation, energy losses, metal consumption, conventional centre of energy loads.

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I. Introduction

More than two thirds of the electrical energy produced in Russia is distributed among industrial consumers. Due to existing requirements in power efficiency the study of power management of industrial power systems is extremely important. Largerly this efficiency is determined by the structure of the system. A typical industrial power system is built as a hierarchy [1-5], with consumer units at the lower level, and the power substations of an industrial unit at the top level. The positioning of the substations influences the structure of the power system and, ultimately, determines its efficiency. Energy losses in power lines, as well as the quality of the power supplied to the consumers also depend on the correct positioning of the substation.

II. OVERVIEW

The existing studies have resulted in guidelines on determining the best positioning of power sources in an industrial unit. Some of the works have more fundamental character and offer generalized mathematical and structural models [4-6], which, as a rule, are used for large, spatially distributed power lines, for example power lines within a geographical area. The problem of power management in works [6, 7] is analyzed using the method of ranking the consumers by the volume of power consumption, the method of 'centre of mass', and further on, their compact positioning is suggested [7-9] so as to prevent energy losses. However, the power sources and power consumers in an industrial power system are located much closer to each other, so the problem needs other solutions. Considering the above mentioned, we can say that the established methods are more suitable for determining the position of the main step-down substation of an industrial unit, but they do not give an answer to the question of the optimal number of power sources considering the factors of energy losses and the cost metal consumption. The production equipment can not always be positioned with regard for the volume of energy consumption, as has been suggested in [8-10]. One has to perform the preliminary cluster analysis of consumers.

III. PROBLEM STATEMENT

The works [4-8] suggest positioning the power substation, when considering the factor of miminizing metal consumption, at the conventional centre of energy loads. Using the accepted methods the coordinates of the centre of energy loads is determined as:

$$\xi_0 = \frac{\sum_{i=1}^{n} P_i x_i}{\sum_{i=1}^{n} P_i} \text{ and } \eta_0 = \frac{\sum_{i=1}^{n} P_i y_i}{\sum_{i=1}^{n} P_i} \qquad (1)$$

where ξ_0, η_0 are the centre coordinates; x_i, y_i are coordinates of i^{th} load; P_i is the power of i^{th} load.

As power consumer units are distributed unevenly within the area, and several centres of loads may have to be determined, it becomes necessary to group the power consumer units, for example, by using cluster method, and then determine the centre in each group [8-10].

Thus, it is necessary to find the coordinates of the centre of energy loads using the method of distributed power density.

IV. THEORY

For the sake of calculations we will use the values of power loads reduced to the prolonged mode S_{pr}.

$$S_{pr} = S_n \cdot \sqrt{TU} \qquad (2)$$

where S_n is the nominal active power of the energy consumer; TU – the time of active use.

The method of distrubuted power density is based on the diffusion of the density of separate units power according to (3):

$$s_{pd}(x, y) = S_{pr} \frac{1}{2\pi\sigma^2} e^{-\frac{(x-a)^2+(y-b)^2}{2\sigma^2}} \qquad (3)$$

where $s_{pd}(x, y)$ is the power density in the point with coordinates x, y, KVA/m2, S_{pr} is the power of a consumer unit, reduced to prolonged mode, (a, b) are the coordinates of consumer units on a plane, σ is the value defining the degree of diffusion of the power density and termed 'radius of diffusion' of power density, m.

According to (3), the power density of each consumer unit is diffused along the dome-like surface. The volume underneath this surface is proportonate to the pwer of the consumer unit.

V. CASE-STUDY OF APPLYING THE METHOD OF DISTRIBUTED POWER DENSITY

The strengths and weaknesses of this method as compared with the methods, that are used now, are exemplified by its application in a machine construction workshop. The workshop equipment includes milling machines, drilling machines, grinding machines, turning machines, overhead cranes, ventillation system, electrical furnace, salt chambers for metal hardening. In both methods coordinates and unit consumption power are used as input data.

Fig.1 illustrates the distribution of power density of all consumer units of the given workshop when $\sigma = 0.2$ m. As following the method conditions the diffusion radius is set as the same for all consumer units, their power will be characterized by the height of the surfaces.

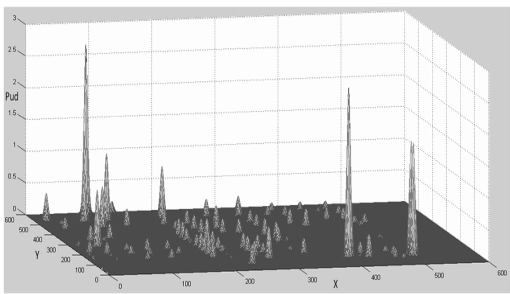

Fig. 1. The surface of distributed power density of energy consumers with small diffusion radius

The diffusion radius σ has to be increased to 15 m for determining the coordinates of the centre of energy loads. Distribution of power density with σ is illustrated by Fig.2.

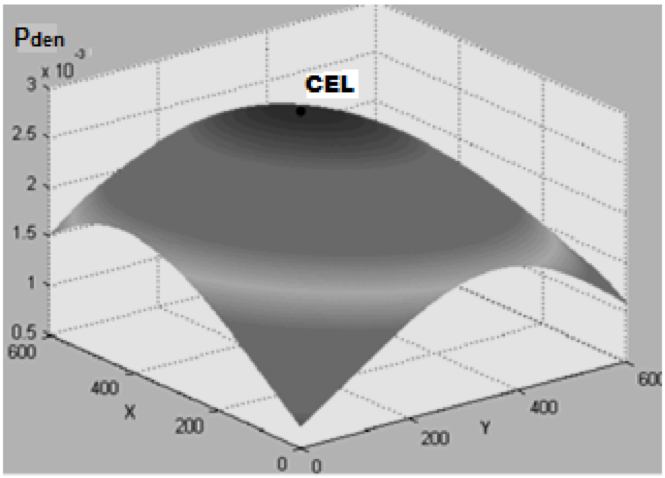

Fig. 2. Distribution of power density when $\sigma = 15$ m

The peak of the resultant surface is projected onto the conventional centre of energy loads according to the description of the method [7,9-12]. The volume of the resultant surface is equal the sum of volumes under the surfaces shown in Fig.1. The established in this way centre of energy loads has the coordinates $x = 32$ m, $y = 25$ m. It should be noted, that the coordinates obtained by the accepted method of the centre of mass coincide with the coordinates given above. That points to the correctness of the method of distributed power density when applied to the positioning of one power substation.

Distribution of power density, as per Fig.1 and Fig.2, are extreme cases of distribution. Distribution with σ σ between 0.2 and 15 m defines the coordinates of the undirected graph nodes of the electrical power system.

The criteria for comparing the methods of determining the centre of energy loads are:

- the amount of energy losses in the industrial power system;

- metal consumption.

VI. Evaluation of Energy Losses

When evaluating the amount of energy losses per transmission with one substation positioned in the cenre of energy loads it will be supposed that each receiver is connected to the source by a single feeder. In practice, this mode is not applied, it can be used, however, for comparison and evaluation of losses [8, 12-14].

The length of single feeders will be determined by the equation:

$$l = \sqrt{(x_i - x_0)^2 + (y_i - y_0)^2} \qquad (4)$$

where $(x_i; y_i)$ are coordinates of the consumer unit; $(x_0; y_0)$ are coordinates of the centre of loads.

Knowing the length of the feeders we can determine the losses per transmission. Total losses of power will be determined as:

$$\Delta P = \sum_{n=1}^{i} I_{ei}^2 \cdot R_i \qquad (5)$$

where I_{ei} is the effective current flowing in the conductor to the i th receiver, R_i – resistance of the i th conductor.

VII. Evaluation of Metal Consumption in Power Lines

Apart from evaluating the energy losses per transmission, it is necessary to evaluate the costs involved in the power supply system installation and maintenance. These costs are defined by the metal consumption during lines installation, that is the amount of metal in the wires of power lines. The metal consumption is determined as a multiple of the wire length by its cross-section. These are the parameters that decide the costs of the power lines. With the metal consumption C_m and wire cross-section s,

$$C_m = \sum_{n=1}^{i} l_i \cdot s_i \qquad (6)$$

where l_i is the length of the i th segment of the line; s_i is the cross-section of the i th segment of the line. The cross-section is chosen on the basis of the condition of permissible current considering the wire heating.

VIII. Results

Having calculated the metal consumption and energy losses, we can obtain the sufficient data on the efficiency of the planned system of power supply. As the coordinates of the centre of energy load, determined by the accepted method and the method of distributed power density, coincide, so the obtained data on power losses and metal consumption will be the same.

For the chosen example in Fig.1 it can be seen, that the biggest power consumer units are located in the industrial unit diagonals. This gives ground to suppose that at certain meaning of σ the distribution of power density forms the double-peak surface. This corresponds to two centre of energy load. This solution can not be obtained by the accepted method.

To get the two-peak surface, the radius of diffusion will be set as $\sigma = 6$ m. The result of distrubution of power density is given in Fig.3.

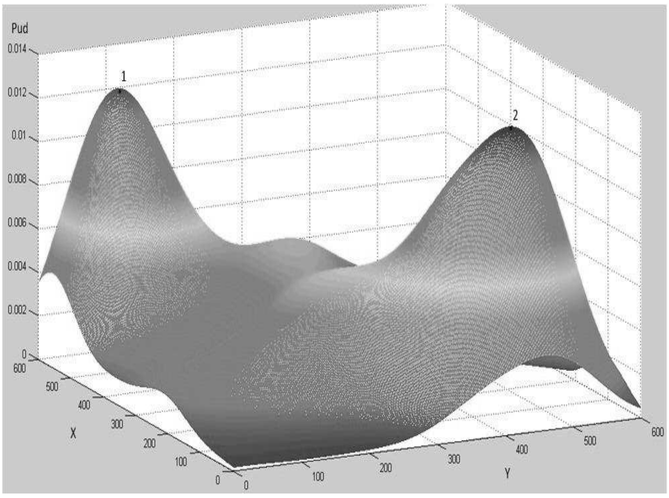

Fig. 3. The distrubution of power density within the area with radius of diffusion $\sigma = 6$ m

Peak 1 has the coordinates $x1 = 53$ $y1 = 11$, peak 2 - $x = 10$, $y = 44$. As the installation of the additional power substation in an industrial unit involves considerable costs, these expenses can cancel out gains obtained by shortening the total length of electricity lines of the power system, it is suggested not to take this course. The transformers power in the power substation should be chosen from the total power of receivers in the whole unit. If the power substation is installed in the first centre of energy loads, then the second centre should host a distribution point supplied by the substation. This course will involve increased costs of distribution point only.

After determining the position for installing the substations, it is necessary to distribute the consumer units between the power sources (substation and distribution point). At present, this problem is usually solved by cluster analysis method [8-10]. Distributed power density method allows to solve this problem as well. The border between connected consumers will be determined by the line of minimal values of power density with the same value of diffusion radius σ. The border obtained in the described way, is given in Fig.4.

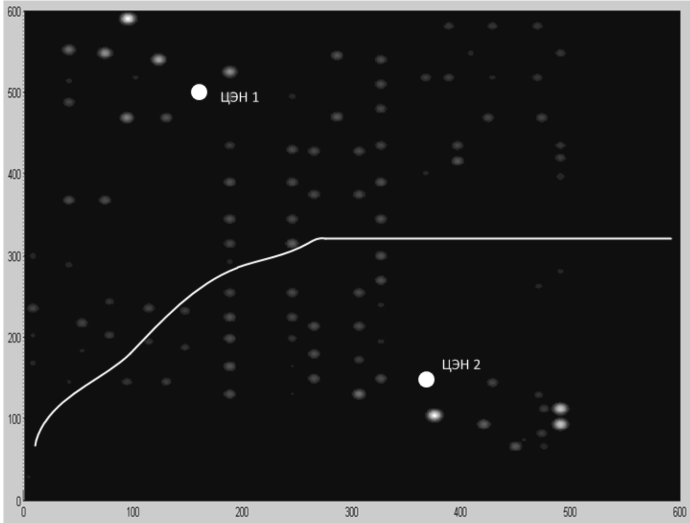

Fig. 4. The borders of connecting the consumers to the substation

Let us assume that the lengths of wires that connect the receivers to the substation are equal to the distance from them to substation and distribution point.

The length of substation consumer wires is

$$l_{1i} = \sqrt{(x_{1i} - x_1)^2 + (y_{1i} - y_1)^2} \qquad (7)$$

The length of distribution point consumer wires is

$$l_{2i} = \sqrt{(x_{2i} - x_2)^2 + (y_{2i} - y_2)^2} \qquad (8)$$

where (x_{1i}, y_{2i}) and (x_{2i}, y_{2i}) are the coordinates of the consumers belonging to the first and the second group simultaneously.

(x_1, y_2) and (x_2, y_2) are coordinates of the power substation and distribution point correspondingly.

IX. Discussion

The metal consumption of the system with two centres of energy loads is proportonate to the total length of the wires, as the cross-sections of the wires feeding the receivers have not changed. This conclusion is true only if it is assumed that the consumers are connected to the power substation and distribution point by single feeders. The metal consumption of the power lines with two centres of energy loads in an industrial unit is determined by the sum:

$$C_m^{'} = C_{m1} + C_{m2} \qquad (9)$$

where $C_m^{'}$ is the total metal consumption of the power lines with two centres of energy demand; C_{m1} is the metal consumption of wires coming from power substation; C_{m2} is the metal consumption of wires coming from distribution points.

In its turn,

$$C_{m1} = \sum_{n=1}^{i} l_{1i} \cdot s_{1i} \tag{10}$$

and

$$C_{m2} = \sum_{n=1}^{i} l_{2i} \cdot s_{2i} \tag{11}$$

where l_{1i}, l_{2i} is the length of wires coming from power substation and distribution point correspondingly, s_{1i}, s_{2i} are the cross-sections of the wires connected to the power substation and the distribution point correspondingly [15, 16].

The calculations show that the savings on metal with two centres of energy demand amounts to 31%.

The power losses per power transmission will be propotonate to the load current and line resistance squared. As load consumtion in an industrial unit will not change with two centres of energy demand, the values of electrical current remain unchanged. The sum of losses per electrical transmission will be proportonate to the metal consumption of he system. Decrease in metal consumtion in this caase is accompanied by the decrease of losses per electrical transmission.

The calculations of energy losses and the comparison of these values for the two studied cases show that the installation of two power substations and distribution points in two centres of energy load decreases the power losses per transmission by 31%.

X. Conclusion

Analyzing the power systems of industrial units shows that the application of the method of ‘centre of mass’ for determining the position of substation is not always efficient, as it allows to determine the position of one substation only for previously grouped power consumers. The preliminary grouping is conducted at random, without considering the optimality criteria. The method of distributed power density, that was described above, allows to design the system of power supply with better characteristics in terms of minimal losses per power transmission and minimal metal consumption. The developed method has universal nature and can be applied in design of systems of power supply of industrial units. On the basis of the conducted studies it is possible to assume that the use of the method of distrubuted power density suits the problem of determining the optimal positions for installing the reactive power compensators. The installation of the latter will give the addional cuts in energy losses and increase the quality of the power supplied to consumer units.

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