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IMPACT OF THE LOAD CURVE ON LOSSES IN THE POWER SUPPLY NETWORK OF THE COMPANY

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In the recent years, the researchers and experts in the field of energetics often mention in their publications a need to reduce power transmission losses. Among different ways to accomplish this goal the method of the company load leveling stands out due to its simplicity, accessibility and efficiency. The paper proposes a new assessment factor for additional power losses in distribution network. It is known that dispersion of the load curve correlates with the amount of power losses, which is why the proposed factor is put in a position of dependency on the shape of the load curve of the company. It is demonstrated that the proposed factor can help to identify without any strain a need in technical measures for levelling the load curve of the company and to assess efficiency thereof.
***Key words*:** load curve, electric power transmission, power regulators, conductor heating factor.

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Introduction. The issues of energy-efficient generation transmission and consumption of electric power are interrelated. Energy generated from organic fuel, i.e. gas, coal, petroleum products, etc., represents a large share of the total volume of energy produced. Besides alternative energy sources are gaining more and more prominence [9, 12, 14].

One of the main integral indicators showing how energy-efficient is the power consumption in the company is the electric load curve [7, 10, 11, 13, 15, 16].

Irregular daily consumption of electric power reduces the energy efficiency of power generation, transmission and consumption. At each of these stages the installation of uprated expensive equipment is required, which is run at its nominal parameters only for a short while.

Additional concern is the increased energy losses in the power supply networks due to irregular load distribution. This significantly affects service life of the power supply networks, especially the cable lines.

Regulated power consumption has a major impact not only on the processes of electric power generation, but also on the processes of its transmission [5]. The task of increasing the production energy efficiency is extremely important and is first of all necessitated by the considerations of competitiveness. The survival of the company, and in some instances of the entire sectors of real economy, quite often depends on efficient pursue of this task. There are numerous ways to increase the energy efficiency, which often imply introduction of new technologies and modification of production process.

Development of an approach to the rational use of energy storage devices based on the original variable load profile can significantly reduce not only the energy consumption costs, but also the costs of its generation.

Modes of operation of the electric power consumers do not remain constant, but all the time change during the day, the weeks and the months [4, 6, 8, 15]. Therefore, the load on all components involved in the power transmission and distribution and on the generators of electric substations changes respectively. Changes in the electric units' load over the time are usually reflected graphically in the form of load curves. There can be the curves of active and reactive loads. By duration, the load curves can be shift, daily and annual. In operating conditions load changes by active and reactive power over time are presented in the form of a step like curve built on readings of the meters of active and reactive power, taken at equal time intervals (30 or 60 minutes).

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The energy efficiency is significantly impacted by the daily load curve of the electrical and engineering complex of the company. Its leveling leads to the reduced fuel specific consumption for electricity generation and lower rated capacity of the power plant to cover the peak loads, and allows to reduce energy losses in the electric power networks [3].

Typical daily electric load curves of the companies from different industries are shown in Fig. 1.

Analysis of presented load curves of the companies from different industries shows that they differ greatly by the evenness of electric power consumption. It can be seen that the energy consumption in oil refining, coal extraction, peat processing, non-ferrous metallurgy, chemical industry, ferrous metallurgy and heavy engineering is even throughout the day. While a significant drop in energy consumption at night is typical for the machinery and repair plants, machine tool enterprises, automotive, wood processing and light industries. The pattern of energy consumption in heavy engineering enterprises, automotive, machine tool, repair and mechanical plants, ferrous metallurgy, peat processing plants is substantially different during the weekend.

Knowledge of the load curves allows to determine the magnitude of cross sections of wires and cable cores, to measure voltage drop, select capacity of power plants' generators, design power supply systems for future facilities, solve problems of technical and economic nature, etc.

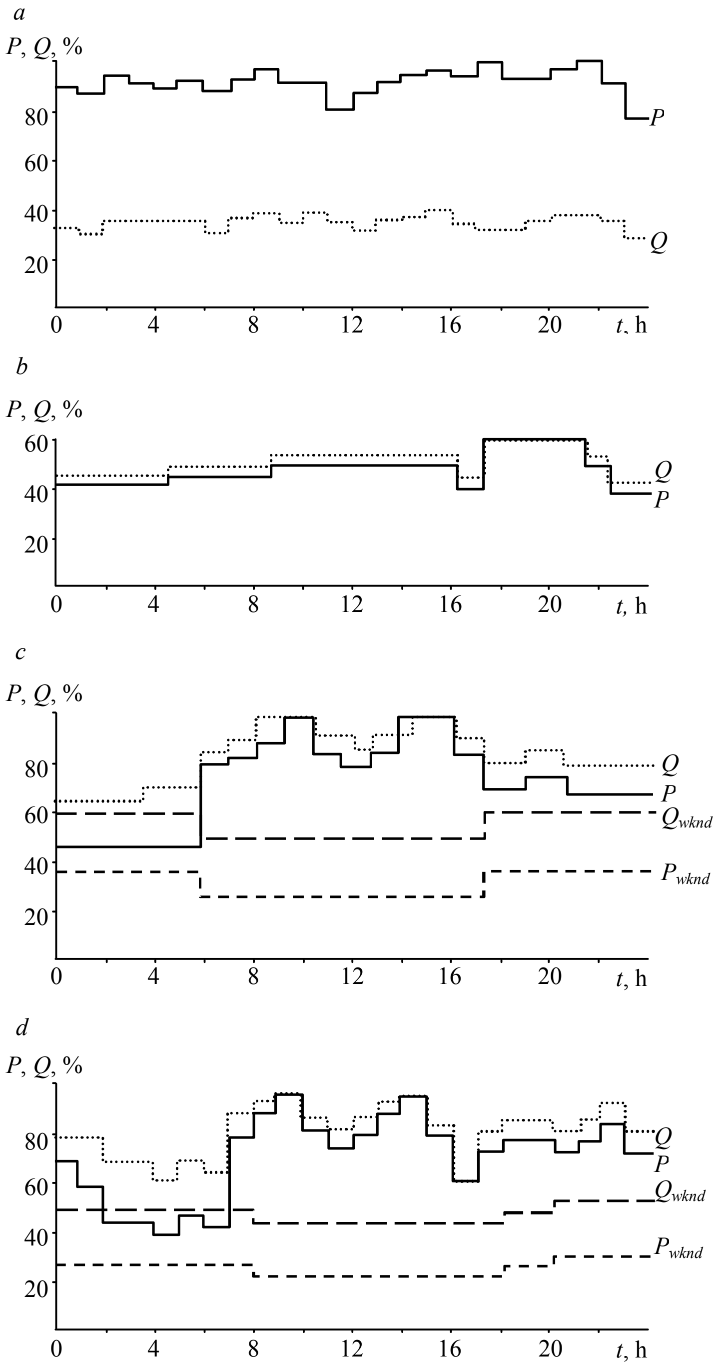

Fig. 1. Typical daily load curve of:
oil refineries (*a*); coal mines (*b*); machine tool plants (*c*);
automotive manufacturing plants (*d*)

Power transmission losses can be included in a separate group, as this issue is typical for the overwhelming majority of the companies. Power losses during transmission deserve special attention in the contex of industrial enterprises, being an extremely negative factor, which cannot be avoided, but which can be reduced by regulating the power consumption. Most power is lost for the thermal heating of conductors, the amount of which is proportional to the square of the current flowing through the conductors.

There is no simple method to assess the reduction in power losses during load curve levelling, which makes calculations a labour intensive process. That's why the objective of studies described in the paper was to identify relationships based on which changes in energy losses in the power supply lines at different modes of company operations can be quickly measured.

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Research methodology. As applicable to the active and reactive power curves, the square of which determines the flow rate of active and reactive energy, the following equation can be used:

$$P_{cT} = \frac{\int_0^T Pdt}{T} = \frac{W_{aT}}{T}; \;\; Q_{cT} = \frac{\int_0^T Qdt}{T} = \frac{W_{pT}}{T}, \tag{1}$$

where P_{cT} and Q_{cT} is the averaged over time T active and reactive power respectively; W_{aT}, W_{pT} is the active and reactive energy consumed over time T.

There is an average current corresponding to the average power over time T

$$I_{cT} = \frac{P_{cT}}{\sqrt{3}U_n \cos\varphi_T}, \tag{2}$$

where U_n is a nominal voltage; $\cos\varphi_T$ is an average weighted value over time T,

$$\cos\varphi_T = \cos(\operatorname{arctg}\frac{W_{pT}}{W_{aT}}). \tag{3}$$

In order to compare energy losses let's examine the simplest example, when equal amounts of electric energy are transmitted evenly over different time, and the load node is connected to the source via line with active resistance R. Let's assume that in the first case current l_1 flows through the conductor and the load node evenly consumes energy $W_н$ over time T_1. Then for this case

$$W_1 = I_1^2 R T_1, \tag{4}$$

where W_1 is the energy loss for conductor heating.

In the second case the load node evenly consumes the same energy W_2, but over longer time T_2 and with current I_2 flowing though the conductor. Then

$$W_2 = I_2^2 R T_2. \tag{5}$$

Let's assume that the load voltage remains constant (U_r = const) in both cases, then

$$U_r I_1 T_1 = U_r I_2 T_2, \tag{6}$$

$$I_2 = \frac{I_1 T_1}{T_2}. \tag{7}$$

The ratio of energy losses can be presented as follows:

$$\frac{W_2}{W_1} = \frac{\int_0^{T_2} P_2(t)dt}{\int_0^{T_1} P_1(t)dt} = \frac{I_2^2 R T_2}{I_1^2 R T_1} = \frac{I_1^2 (\frac{T_1}{T_2})^2 R T_2}{I_1^2 R T_1} = \frac{T_1}{T_2}. \tag{8}$$

Expression (8) shows that in the simplest case of load leveling the power consumed for heating of the conductors, is characterized by the ratio of load feed time. It is obvious, that for calculation of reduction in losses an expression can be used, which we define as the conductor heating factor $K_{нп}$. In case of maximum load leveling for even consumption the index 'м' shall be added $K_{нпм}$. Conductor heating factor in a general way can be presented by the formula as follows

$$K_{нп} = 1 - \frac{W_2}{W_1} = 1 - \frac{\int_0^{T_2} P_2(t)dt}{\int_0^{T_1} P_1(t)dt} = 1 - \frac{I_2^2 R T_2}{I_1^2 R T_1} = 1 - \frac{I_1^2 (\frac{T_1}{T_2})^2 R T_2}{I_1^2 R T_1} = 1 - \frac{T_1}{T_2}. \tag{9}$$

Let’s examine the following example. The load node evenly consumes energy for 10 hours. If the consumption is evenly distributed over 24 hours, then

$$K_{\text{нп}} = 1 - \frac{T_1}{T_2} = 1 - \frac{10}{24} = 0.58. \tag{10}$$

In other words, losses for conductors heating are reduced by 58%.

In practice even load patterns are very rare, usually load pattern with averaging interval is used ($T_{\text{оср}}$ is the averaging time). In this case, the factor will take the following form

$$K_{\text{нп}} = 1 - \frac{\sum_{i=1}^{n} P_{i2} T_{\text{оср}}}{\sum_{i=1}^{n} P_{i1} T_{\text{оср}}}, \tag{11}$$

where i is the step of load curve; P_{i1} and P_{i2} are the steps of power of the first and the second load curves respectively.

In order to calculate all heating losses, resultant from unevenness of the load, let’s find a relationship between $K_{\text{нпм}}$ and shape factor $K_{\text{ф}}$, and for this let’s carefully examine the following expressions.

Mean square load for a certain period of time is determined by the following expression

$$P_{\text{э}T} = \sqrt{\frac{1}{T}\int_0^T [P(t)]^2\, dt}\,. \tag{12}$$

Similar expressions can be built for the gross power and current. Mean square load reflects the effect of conductor heating by the current, that’s why it is often called the effective load (which explains index ‘э’ in the symbol denoting the mean square load). Based on expression (12) the apparent conclusion is that if the load pattern is uneven mean square load $P_{\text{э}T}$ is always higher than the average P_{cT}, and it is further increased with the growing unevenness of the load curve, i.e. at peak loads [2].

Determination of the mean square (effective) load with the given stepped curve is reduced to calculation by the below formula

$$P_{\text{э}} = \sqrt{\frac{\sum_{i=1}^{n} P_i^2}{n}}, \tag{13}$$

where P_i is the active power for a period; n is a number of periods of equal duration.

Average power

$$P_{\text{с}} = \frac{\sum_{i=1}^{n} P_i}{n}. \tag{14}$$

It is known, that the ratio of $P_{\text{э}}$ to $P_{\text{с}}$ defines the shape factor:

$$K_{\text{ф}} = \frac{P_{\text{э}}}{P_{\text{с}}} = \sqrt{n}\,\sqrt{\frac{\sum_{i=1}^{n} P_i^2}{(\sum_{i=1}^{n} P_i)^2}}. \tag{15}$$

The structure of expression (15) implies that $K_{\text{ф}}$ value increases at the load curve peak. That’s why for several power consumers operating in intermittent mode, this value will be higher than for a group of such power consumers [1].

The shape factor characterizes the losses for conductor heating with uneven consumption relative to the even load. In order to find relationship between $K_{\text{ф}}$ value and energy losses in the network, the following equation was derived

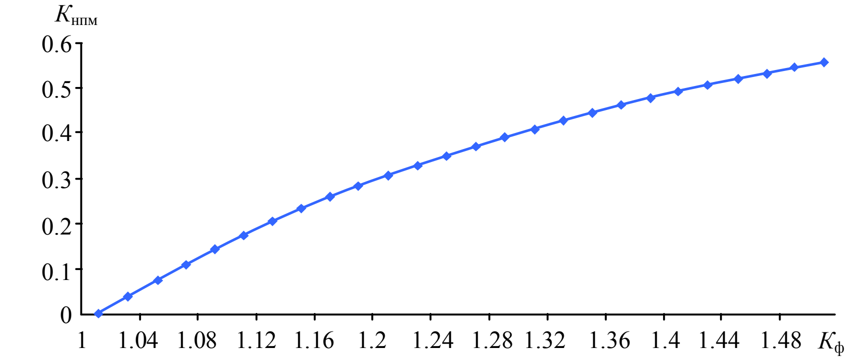

Fig. 2. Relationship between $K_{\text{нпм}}$ and $K_{\text{ф}}$

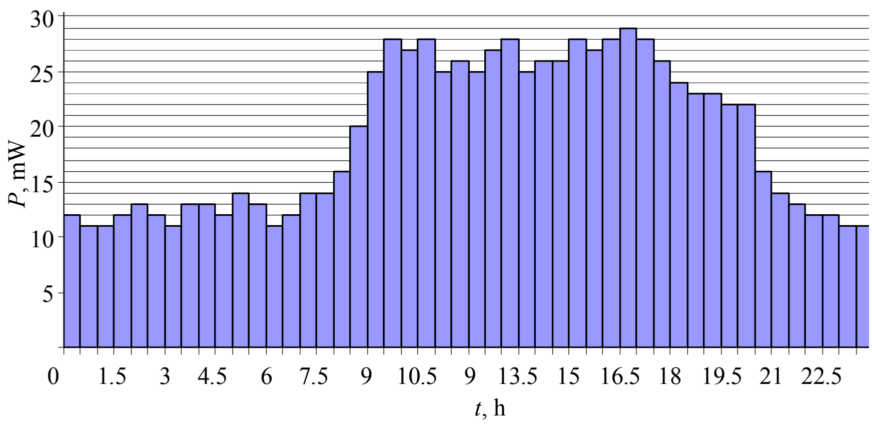

Fig. 3. Daily load curve of industrial enterprise

$$K_{\text{нпм}} = 1 - \frac{1}{K_{\text{ф}}^2}. \qquad (16)$$

In other words the relationship between changes in losses resultant from the curve unevenness in the load feeding network and the shape factor has been obtained.

Scientific and practical findings. Fig. 2 by way of an example shows dependency relationship between $K_{\text{нпм}}$ and $K_{\text{ф}}$.

It shall be noted that the reduction of losses within the load node will be probably higher than in the feeding lines. The explanation is that the load node generally consists of smaller load nodes, which in their turn consist of separate consumers, the load curves of which are more uneven and have the higher shape factor.

Let's examine an example of the daily load curve of an industrial enterprise (Fig. 3).

Effective power value

$$P_{\text{э}} = \sqrt{\frac{\sum_{i=1}^{n} P_i^2}{n}} = \sqrt{\frac{19813}{48}} = 20{,}316 \text{ mW}.$$

Average power value

$$P_{\text{c}} = \frac{\sum_{i=1}^{n} P_{\text{i}}}{n} = \frac{919}{48} = 19{,}145 \text{ mW}.$$

Shape factor

$$K_{\text{ф}} = \frac{P_{\text{э}}}{P_{\text{c}}} = \frac{20{,}316}{19{,}145} = 1{,}061.$$

Conductor heating factor (maximum)

$$K_{\text{нпм}} = 1 - \frac{1}{K_{\text{ф}}^2} = 1 - \frac{1}{1{,}061^2} = 0{,}111.$$

Analysis of research results. As evidenced by the analysis of the research results, 11.1% of heating losses in the feeding lines can be avoided by the load curve levelling. It can be stated that the analogous losses in the internal network of the company are most likely exceeding 11.1%.

The obtained dependency relationship between $K_{\text{нпм}}$ and $K_{\text{ф}}$ helps to quickly assess changes in the losses within the power supply network when the power consumption gets levelled. To do this the load curve of the company shall be examined, while availability of power supply circuits is op-

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tional. Thus it follows that losses in the electric networks can be substantially reduced by levelling the load curve, which can considerably reduce the energy losses and increase the energy efficiency of the enterprise.

Conclusions. The proposed approach addresses a task of reducing the energy losses by levelling the company load curve. The loss change factor $K_{\text{нпм}}$ introduced as a criterion for assessing efficiency of the load curve levelling reliably reflects the impact of introduced changes. This factor is also a criterion for assessing the need in technical measures for regulating the load at the industrial enterprises.

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