Comprehensive assessment of factors determining electricity load curves concerning enterprises of mineral resource sector

D A Ustinov and K A Khomiakov
Saint-Petersburg Mining University, 2, line 21 V.O., St. Petersburg, Russia, 199106
E-mail: Kostyhom@gmail.com

Abstract. The efficiency of enterprises run in the scope of the mineral resource sector is largely determined by the effectiveness of a power supply system. Therefore, the article sets out to supplement a new information database containing the source data basing on a mathematical model of the random process. A brief description of the mathematical model of the random process that defines normalized correlation functions and its parameters at the level of individual energy consumers is presented. A feature of the study is that consumers are considered with and without a variable speed drive. Quantitative data on the difference in the parameters of the same consumers are presented both with and without regulation. It is concluded that it is relevant to supplement the information database.

1. Introduction
The problem of improving the methods for calculating the characteristics of electricity load curves of power supply systems is rather relevant. The efficiency of power supply systems of industrial enterprises is determined by the reliability of the calculated values as early as at the design stage and it determines the technical and economic feasibility study of an enterprise. Thus, the reliability of assessing the estimated values of electricity load curves characteristics is quite relevant while designing centralized power supply and even more relevant in the creation of autonomous power supply systems, which are currently finding ever-widening applications in enterprises of the mineral resource sector.

2. Probabilistic calculation method using principle of mathematical model of random process
The purpose of the probabilistic method based on the principle of a mathematical model of a random process is to determine the type and parameters of normalized correlation function $R(t)$ of individual industrial energy consumers, which constitute the main load of energy consumers at the enterprises of the mineral resource sector. The obtained values form the source data base. It is worth noting that the type and parameters of normalized correlation functions substantially determine the effect of conductor heating, and, as a result, the calculated values of heating loads, peak loads, the rate of changing load schedules ordinates, emissions, dips and load fluctuations.
It is necessary to identify a number of initial assumptions that underlay the experimental evaluation of the normalized correlation functions:
1. Stationarity of the random process of electric energy consumption in the busiest shift $T_{sh}$ or during the complete complex technological cycle $T_C$. 
2. Normality of the ordinates probability distribution law with regards to the random process concerning electrical load changing.

3. Independence of random processes concerning changes in the electrical load of individual energy consumers involved in forming a load group curves.

According to several works, it was revealed that all the types of load schedules can be approximated by the following normalized correlation functions [1]:

\[
K(t) = DP_{\exp}(-\alpha|\tau|); \\
K(t) = DP_{\exp}(-\alpha|\tau|)\cos\omega_0\tau; \\
K(t) = DP_{\exp}(-\alpha|\tau|)(\cos\omega_0\tau - \frac{\alpha}{\omega_0}\sin\omega_0|\tau|); \\
K(t) = DP_{\exp}(-\alpha|\tau|)(\cos\omega_0\tau + \frac{\alpha}{\omega_0}\sin\omega_0|\tau|). 
\]

where parameter \(\alpha\) characterizes the attenuation of the probabilistic relationship between the ordinates of the initial load curves, while the parameter \(\omega_0\) characterizes the natural frequency of normalized correlation functions oscillations due to the technological operations repetitiveness.

The studies in the field of electricity loads enable to conclude that the random process of load distribution refers to an ergodic random process. The fact that the process belongs to a stationary random process and is ergodic in nature is checked at the stage of experimental research and is proved mathematically. Otherwise, if a schedule is characterized by non-stationarity, it is necessary to select stationary sections and evaluate the calculated parameters on it.

The normalized correlation functions were evaluated experimentally with regards to the following stages: the stage of preliminary experiment planning and the stage of the obtained data processing. The purpose of the experiment planning stage was to obtain additional information about random electrical load graphs in order to facilitate the experimental estimation of normalized correlation functions in subsequent stages. As a result the preliminary values of the recording time of the process \(T_{pr.r.}\) and the sampling interval of the original graph were obtained.

It is important to note that a short recording time \(T_r\) will not provide the necessary accuracy in the estimation of statistical characteristics, while excessive recording time will lead to stationarity violation. The same applies to the sampling interval \(\Delta t\), the decrease of which will lead to redundancy, and increase to the loss of information about the random process of electricity load curves changing [2, 3]. Therefore, the choice of these parameters should be justified. The formula for determining the recording time requires knowledge of several statistical characteristics. They are as follows:

\[
T_r = \frac{2\alpha^2T_{cor}}{p^2\eta^2}, \\
T_r \geq \frac{4T_{cor}}{\eta^2},
\]

where \(\eta\) is a relative root-mean-square error of normalized correlation functions calculation under the conditions of the load random curve discretization.

However, the relative root-mean-square error \(\eta\) is determined at the same recording time \(T_{r.r.}\) To solve this problem, it was proposed to select the recording time by the approximate value of the correlation \(T_{cor}\) time, and only the next step aimed to determine the normalized correlation functions [4].

Applying the method of random process singularities greatly simplifies the calculations. The importance of the method of singularities is that characteristics are gained independently of normalized correlation functions, and also contains additional a priori information.
And the first step is to determine the approximate value of the average power $P_{av}$, which is equal to a half-sum of the maximum and minimum values according to the initial load schedule.

$$P_{av} \approx 0,5(P_{\text{max}} + P_{\text{min}});$$

(7)

Next, we determine the average number of intersections $n_{av}$ with the load graph of the average load $P_{av}$,

$$n_{av} = \frac{N}{T_{pr,r}};$$

(8)

where $T_{pr,r}$ is pre-recording time spent on the number of intersections equal to N.

According to an approximate estimate, we also obtain the approximate value of the correlation time $T_{cor}$:

$$T_{cor} = \frac{T_{pr,r}}{\pi \sqrt{2N}} = \frac{1}{\pi \sqrt{2n_{av}}} = \frac{0,22}{n_{av}};$$

(9)

The sampling interval is determined at the stage of the normalized correlation functions experimental evaluation according to the following formula:

$$\Delta t \leq \frac{2}{\pi n_{av}} \sqrt{2} \eta;$$

(10)

After transformations, the equation takes the following form:

$$\Delta t \leq \frac{0,13}{n_{av}};$$

(11)

The required recording time is found by the following expression:

$$T_{r} \geq 80 T_{cor};$$

(12)

3. Theoretical basis for selecting sampling interval of electric load graph

The initial data for calculating the electricity loads are the nominal load of an individual consumer $p_n$, utilization coefficient $k_u$, and the tangent $tg \phi$, as well as additional ones such as the type of normalized correlation function and its parameters. The latter depend on the accuracy of the value of the sampling interval $\Delta t$, which is defined in sampling theorem:

$$\Delta t \leq \frac{1}{2f_{\text{max}}};$$

(13)

where $f_{\text{max}}$ is the maximum frequency of the random stationary process spectrum.

According to the recommendations in [5, 6], the sampling interval should correspond to the fact that the full period with the highest harmonic frequency is part of a random stationary process and it accounts for about 5-20 points. However, due to the fact that the real values of the load graphs have an unlimited spectrum of a random process, determining the maximum frequency above which has no significant effect on the nature of changes in normalized correlation functions is difficult. Therefore, at the planning stage of the experiment, it is necessary to apply another way to solve this problem.

The best solution to this problem is to find the sampling interval according to the condition of restoring the original load curve taking into account the given error [7]. Therefore, we replace the continuous load curve with a discrete one with regards to the root-mean-square error $\delta(\Delta t)$, which is determined by the following expression:

$$\delta^2(\Delta t) = M[P_{st}(t) - P(t)]^2;$$

(14)

where $P_{cm}(t)$ is step load graph with the step length equal to $\Delta t$.

After conversions on the right side we get the following:

$$M[P_{st}(t)]^2 = M[P(t)]^2 = K(0), \ M[P_{st}(t)P(t)]^2 = K(\tau);$$

(15)
Let us write the equation (15) taking into account (16):

$$\delta^2(\Delta t) = 2[R(0) - R(\Delta t)]^2;$$  \hspace{1cm} (16)

where $R(0), R(\Delta t)$ are normalized correlation functions numerical values with $\tau$ equal to 0 and $\Delta t$.

The research resulted in obtaining the equations for determining a sampling interval for all normalized correlation functions, with the condition that for a type of a normalized correlation function (1) it is explicitly solvable:

$$\Delta t = -\frac{1}{\alpha} \ln \left(1 - \frac{\delta^2(\Delta t)}{2}\right) = -T_{cor} \ln \left(1 - \frac{\delta^2(\Delta t)}{2}\right);$$  \hspace{1cm} (17)

And for normalized correlation functions of the type (2-4), it is impossible to solve the equation to find a sampling interval in explicit form:

$$e^{-a\Delta t} \cos \omega_0 \Delta t + \frac{\delta^2(\Delta t)}{2} - 1 = 0;$$  \hspace{1cm} (18)

$$e^{-a\Delta t} (\cos \omega_0 \Delta t + \frac{1}{\kappa_\omega} \sin \omega_0 \Delta t) + \frac{\delta^2(\Delta t)}{2} - 1 = 0;$$  \hspace{1cm} (19)

$$e^{-a\Delta t} (\cos \omega_0 \Delta t - \frac{1}{\kappa_\omega} \sin \omega_0 \Delta t) + \frac{\delta^2(\Delta t)}{2} - 1 = 0;$$  \hspace{1cm} (20)

Therefore, the solution of these equations is possible, for example, by the numerical method of Newton with respect to $\Delta t$ and taking into account that $\delta(\Delta t)$ equal to 5, 10 and 15%.

As a result of all the theoretical studies, it was revealed that this method provides the most reliable assessment of the load graph dynamic characteristics. As a recommendation, it was proposed to take the sampling interval $\Delta t$ of the initial load graphs equal to $0.01 T_{cor}$, to a precision of $\delta(\Delta t)$ 5%.

4. Determining type and parameters of normalized correlation functions of electric load graphs

After conducting research and obtaining the experimental dependences of normalized correlation functions, the approximation using analytical expressions is required (1-4).

For normalized correlation functions of type (1), it is necessary to find only the parameter characterizing the attenuation of the probabilistic relationship between the ordinates of initial load graphs $\alpha$. In other cases, the task is reduced to finding two unknown parameters $\alpha$ and $\omega_0$ of the experimental normalized correlation functions with regards to the characteristic starting points [8]. For normalized correlation functions of type (2), two methods are applicable.

The first method is based on the condition that the ordinates of the experimental and theoretical normalized correlation functions coincide at the corresponding points $\tau$ and $\tau$ of the first minimum.

With regards to the resulting system of equations, the following is true:

$$\begin{align*}
R_2(\tau_1) &= \exp(-\alpha |\tau_1|) \cos \omega_0 \tau_1 \\
R_0(\tau_2) &= \exp(-\alpha |\tau_2|) \cos \omega_0 \tau_2
\end{align*}$$  \hspace{1cm} (21)

Where $\omega_0 = \frac{\pi}{2\tau}$ is obtained by the following way:

$$\alpha = -\frac{1}{\tau_2} \ln \left(\frac{R_0(\tau_2)}{\cos \left(\frac{\pi \tau_2}{2\tau}\right)}\right);$$  \hspace{1cm} (22)

The solution obtained with relation to the second method obtains the values at which an experimental normalized correlation function at point $\tau_2$ turns to zero, and at point $\tau_1 = \tau_2$ turns to 2.

Moreover, the system of equations (21), taking into account $\omega_0 = \frac{\pi}{2\tau}$, results in the following formula:

$$\alpha = -\tau_2^{-1} \ln \left(\sqrt{2} R_0(\tau_1)\right);$$  \hspace{1cm} (23)
To find the parameters $\alpha$ and $\omega_0$ corresponding to normalized correlation functions of types (3) and (4), the values of an experimental normalized correlation function at which $\tau_1$ and $\tau_2$ will take the first and second zero values \[9\] are fixed.

Assuming that $T = 2(\tau_1 - \tau_2)$, and in case of taking into account the natural vibration frequency $\omega_0 = \pi/(\tau_1 - \tau_2)$ we obtain the following expressions:

$$
cos\omega_0\tau_1 + \frac{\alpha}{\omega_0} \sin\omega_0|\tau_1| = 0; \tag{24}
$$

$$
cos\omega_0\tau_1 - \frac{\alpha}{\omega_0} \sin\omega_0|\tau_1| = 0; \tag{25}
$$

Which take the following form after conversion:

$$
\alpha = -\omega_0\text{ctg}\omega_0\tau_1 \tag{26}
$$

$$
\alpha = \omega_0\text{ctg}\omega_0\tau_1 \tag{27}
$$

When the type of an experimental normalized correlation function is unknown beforehand, the value at which the graph reaches the first zero and minimum values will be random, and therefore, the parameters determined by the above methods will not be reliable. The way out of this situation is to apply the least squares method under the condition of minimum quadratic inaccuracy according to the following expression:

$$
\Delta = \int_0^\tau [R_0(\tau) - R(\tau, \alpha_1 ... \alpha_n; \omega_0 ... \omega_n)]^2 dt = \min \tag{28}
$$

The integration limits are from 0 to $\tau = \tau_1$ or $\tau = \tau_2$.

The calculated parameters of the normalized correlation functions enable to recalculate the values of the correlation time $T_{\text{cor}}$ for the normalized correlation functions of the types (1-4) according to the following expressions \[10, 11\]:

$$
T_{\text{cor}} = \alpha^{-1}; \tag{29}
$$

$$
T_{\text{cor}} = \frac{1}{\alpha} - \frac{\omega_0}{\alpha(\alpha^2 + \omega_0^2)} \left(\omega_0 - \frac{2ae^{\frac{\alpha\pi}{\omega_0}}}{1 - e^{-\frac{\alpha\pi}{\omega_0}}}\right); \tag{30}
$$

$$
T_{\text{cor}} = \left((1 - e^{-\frac{\alpha\pi}{\omega_0}})\sqrt{\alpha^2 + \omega_0^2}\right)^{-1} \cdot \frac{\alpha}{\omega_0} \text{arctg} \frac{\alpha}{\omega_0} \cdot \frac{\pi}{2}; \tag{31}
$$

$$
T_{\text{cor}} = \frac{2e^{-\frac{\alpha\pi}{\omega_0}} \text{arctg} \frac{\alpha}{\omega_0}}{\sqrt{\alpha^2 + \omega_0^2}} \cdot \left[1 - \frac{e^{-\frac{\alpha\pi}{\omega_0}}}{\text{arctg} \frac{\alpha}{\omega_0}} + \frac{\alpha}{\omega_0} \text{arctg} \frac{\alpha}{\omega_0}\right]; \tag{32}
$$

At the final stage, with regards to the recalculated correlation time, the recording time and the sampling interval are refined for the initial load curve.

Experimental studies aimed to determine a normalized correlation function and its parameters of the electric load curves were carried out at the existing enterprises of the mineral resource sector, the major part of which are general industrial energy consumers. A feature of the research is that the general industrial drives were compared qualitatively both with and without applying a variable frequency drive. As an example, the initial curves and a phased determination of the type and parameters of normalized correlation functions for a conveyor installation were given. The necessary data were registered in the following sequence:
1. The initial 5 minutes record at the stage of the experiment preliminary planning enabled to determine the value of the average load $p_{av}$ by expression (7).

**Table 1.** Approximate average power

|                      | Without variable speed drive system | With variable speed drive system |
|----------------------|-------------------------------------|----------------------------------|
| $p_{av}$             | 200 kW                              | 180 kW                           |

2. The second record was aimed to register the number of intersections $N = 25$ by the average load level

3. Using expressions (10, 11, 12), we determined the preliminary values of correlation time $T_{cor}$, sampling interval $\Delta t$, and recording time $T_{rec}$ from the initial load curve. Next, we calculate the experimental normalized correlation functions using the MatLab application package [12].

**Table 2.** Preliminary estimated values

| Preliminary values of correlation time $T_{cor}$ | Sampling interval $\Delta t$ | Recording time $T_{rec}$ |
|------------------------------------------------|-----------------------------|---------------------------|
| Without variable speed drive system            | With variable speed drive system | Without variable speed drive system | With variable speed drive system |
| $206\, s$                                       | $19\, s$                    | $121\, s$                 | $11\, s$                      |
| $16480\, s$                                     |                             | $1520\, s$                |                               |

**Figure 1.** Active power consumption without speed control
4. We determined the preliminary theoretical normalized correlation functions basing on the expressions (22, 23, 26, 27)

| Preliminary theoretical normalized correlation functions without variable speed drive system | Preliminary theoretical normalized correlation functions with variable speed drive system |
|---------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|
| $R(\tau) = \exp(-0.0099|\tau|)\cos(0.01298\tau)$ | $R(\tau) = \exp(-0.0444|\tau|)\cos(0.1428\tau)$ |

**Figure 2.** Active power consumption with speed control

**Figure 3.** Preliminary theoretical normalized correlation functions without speed control
5. The correlation time $T_{\text{cor}}$ and the recalculation of the recording time $T_{\text{rec}}$ and the sampling interval $\Delta t = 0.01T_{\text{cor}}$ were determined using the expressions (29, 30, 31, 32).

Table 4. Refined calculated values

|                      | Correlation time $T_{\text{cor}}$ | Sampling interval $\Delta t$ | Recording time $T_{\text{rec}}$ |
|----------------------|-----------------------------------|------------------------------|---------------------------------|
| Without variable speed drive system | 69.5 s                           | 14.5 s                       | 5560 s                          |
| With variable speed drive system       | 69.5 s                           | 14.5 s                       | 5560 s                          |

6. We recalculated the parameters of the theoretical normalized correlation function and got its final form taking into account the adjusted values necessary for the calculations and using the least square method.

Table 5. Refined theoretical normalized correlation functions

| Theoretical normalized correlation function without variable speed drive system | Theoretical normalized correlation function with variable speed drive system |
|---------------------------------------------------------------------------------|--------------------------------------------------------------------------|
| $R(\tau) = \exp(-1.723|\tau|)\cos(2.26\tau)$                               | $R(\tau) = \exp(-3.37|\tau|)\cos(10.23\tau)$                               |
5. Conclusion
The conducted studies prove that the common industrial power supply units belong to the same type of normalized correlation functions with and without using a variable frequency drive but the difference is in the parameters of normalized correlation functions that determine the calculated values of the power supply system as a whole. As a result, there is a need to supplement the new information database.

Also, at the stage of preliminary planning the article recommends to determine the experimental evaluation of the normalized correlation functions of the sampling interval of the electric load initial graph by the expression $\Delta t \leq \frac{0.13}{n_{av}}$, and implementation duration by the expression $T_{rec} \geq 80T_{cor}$.
References

[1] Zhezhelenko I V, Saenko Y L and Stepanov V P 1998 Methods of probabilistic modeling in the calculation the characteristics of electrical loads of consumer (Samara: Energoatomizdat)
[2] Skamyin A N and Belsky A A 2017 Reactive power compensation considering high harmonics generation from internal and external nonlinear load IOP Conference Series: Earth and Environmental Science 87(3) 1-6 DOI:10.1088/1755-1315/87/3/032043
[3] Reshneva E, Ponomarenko T V 2019 Challenges and opportunities of integration of the energy capacity of the republic of moldova (Rm) in the european energy system Topical Issues of Rational Use of Natural Resources - Proceedings Of The International Forum-Contest of Young Researchers 325-328
[4] Stepanov V P, Krotkov E A, Vedernikov A S and Gudkov A V 2006 On reason of overestimate of peak and valley of load curve for engineering plant Industrial Power Engineering 1 27-30
[5] Wentzel E S 1964 Probability Theory (Moscow: Nauka)
[6] Lenge F 1963 Correlationselectronik (Leningrad: Sudpromgiz)
[7] Krotkov E A and Stepanov V P 1998 Theoretical substantiation of the sampling interval for calculation the correlation functions of electric load graphs Power engineering control quality and energy efficiency (Blagoveshchensk: Amurskaya pravda) 70-74
[8] Safiullin R, Marusin A, Safiullin R and Ablyazov T 2019 Methodical approaches for creation of intelligent management information systems by means of energy resources of technical facilities E3S Web of Conferences 140 DOI: 10.1051/e3sconf/201914010008
[9] Keka I, Betim C and Neki F 2017 Effect of parallelism in calculating the execution time during forecasting electrical load JNTS 44 169-179
[10] Kumar D and Samantaray S R 2014 Design of an advanced electric power distribution systems using seeker optimization algorithm International Journal of Electrical Power & Energy Systems 63 196-217
[11] Y Yamagata 2015 H Seya Proposal for a local electricity-sharing system: a case study of Yokohama city Japan IET Intell. Transp. Syst. 9 38-49.
[12] Nedosekin A O, Rejshahrit E I and Kozlovskij A N 2019 Strategic approach to assessing economic sustainability objects of mineral resources sector of Russia Journal of Mining Institute 237 354-360 DOI: 10.31897/pmi.2019.3.354