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Model studies to identify input parameters of an algorithm controlling electric supply/consumption process by underground iron ore enterprises

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Abstract

Purpose is the development of the research format of a mathematical model to select and assess input parameters of an algorithm controlling distribution of electric energy flows in the monitoring structure of electricity supply/consumption by using equipment of mining enterprises engaged in underground iron ore raw materials extraction.

Methods. The analytical research involved a theory of random processes adapted to the real conditions. For the purpose, results of experimental measurements have been applied obtained under the conditions of active iron ore enterprises using underground procedures of the raw materials mining. Methods of random functions (i.e. elements of correlation theory) have helped identify the basic input and output parameters characterizing rather completely electric supply consumption as a stochastic process to develop a control algorithm for the process.

Findings. A mathematical model of an electric supply/consumption complex as a stochastic process has been developed to assess its features as well as its levels of influence on the economic operational indices of electric power system of underground mining enterprises. Formation of the algorithm to control distribution of electric power flows among consumers of the analyzed types of iron ore enterprises took into consideration stochastic nature of the mentioned complex activity.

Originality. The procedure of electric supply/consumption by underground iron ore enterprises has been analyzed in the format of process of a stochastic process of their operation. For the first time, the synthesized mathematical model has been built; both average and disperse stochastic characteristics of electric consumption capacity have been identified; average period of electric energy consumption as a stationary random function during the specified time has been determined; and average number of electric consumption peaks for the interval has been defined as well as average duration of their surges. Analysis of the electric supply/consumption process as a stochastic process has helped solve a problem of the peak influence on the modes of electric energy consumption by receivers of the enterprises, i.e. the random function crossing the specified electric consumption level.

Practical implications. According to the available computing formats, a calculation procedure of the operation parameters of electric supply/consumption is of insufficient accuracy since average values are applied and stochastic nature of the process is ignored, which is typical for the analyzed mining enterprises. The abovementioned restricts the possibility to develop adequate system to control the electric power process in terms of the types of mining enterprises and specificity of their operational technology. The developed methods of electric supply/consumption functioning dynamics as a stochastic process help expand its use while forming and making efficient managerial decisions in the context of the analyzed process.

Keywords: *model, electric supply, electric consumption, stochastic nature, assessment, random process, mining enterprise*

1. Introduction

The current techniques of surface (open pits) and underground (mines, ore workings) extraction of iron ore raw materials (IORMs), being the basic Ukrainian type of minerals as well as the basic export material of the state, are the examples of non-energy efficient technologies influencing negatively the prime cost of its extraction [1], [2]. Hence, it is required to solve the problem of decrease in energy intensity of IORMs extraction. Moreover, in the format of the current techniques, a natural process of mining deepening factors inevitably into stable increase of energy segment in the complex of the extracted IORMs [3]-[5].

If adequate decisions are not made, the situation may become tragic for Ukraine since it will have to leave the world market of raw materials stopping its role as an active player in the field of IORMs export, and their metallurgical redistribution.

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The present, being a segment of tolerant time uncertainty of a problem as for the increase in the electric power efficiency of the domestic industrial enterprises on the whole, and mining ones in particular, dictates severely the necessity to make the promptest decisions in terms of the political and economic tendency being important for Ukraine.

The enforcement of the Law of Ukraine [6] creates potentially real possibilities to implement programs of the improved energy efficiency of enterprises in the state. Thus, according to the abovementioned Law, intraday segment of the electricity market is under development with hourly prices per day forward. In this context, each following day, prices vary depending upon bidding results, i.e. electricity purchase and sale in the energy market of the state. Such an approach provokes significant uncertainty in the activities by consumers who plan their long-term operations relying upon their logistics. Such enterprises involve mining and metallurgical companies; among other things, those ones engaged in underground ore extraction.

In the final format, determination of the required transition to the day ahead level of electric energy (EE) consumption influences greatly correctness of iron ore extraction cost by a customer, applying for such an energy type. In turn, either unsubstantiated or poorly substantiated request will not be successful for the current economy of the enterprise. To minimize the problems, one should change the available approaches as for labour organization in the power sector of the enterprise, and as for the actual monitoring and control of EE consumption during hours of each current day.

Introduction of the system to control EE consumption is a difficult task; it becomes a challenge if option of a manual control mode is implemented; what is more, it may become unrealistic. It is quite reasonable to perform the operation automatically on the platform of an adequate automated control system (ACS). In this vein, its efficiency will depend upon soundness as well as the developed proper functioning algorithm. The latter will be sufficient to make energy efficient decisions in terms of correct development of input parameters for the ACS operation. In such a way, the topical task is formulated to develop a control system based upon preventive assessment and processing of input data complex with further proper command giving.

To solve such problems and obtain real solution, it is required to involve several optimization methods inclusive of mathematical modelling. However, to have results of the desired reality level, logistics of the research should represent the electric power process as a dynamic complex being electric supply/consumption (ESC). At present, there is no analysis of such a research block, which prevented from assessment of input parameters with the required accuracy, and receiving of the final result to develop relevant ACS with necessary efficiency [7].

In this context, it is important to understand that the development of further research tactics should rely upon the idea that functioning processes of ESC complex of iron ore mines differ greatly from technological analogue of the types of coal mining enterprises as well as other ones [8].

1.1. Review of scientific sources and statement of the problem

While summarizing (in the format of the paper structure) history of archival scientific inquiries in the list of methods to improve energy efficiency of IORMs extraction under the conditions of underground iron ore enterprise specificity, it is necessary to mention the topic is "eternal"; nevertheless, time corrects and changes both its format and research methods.

The outlook has shaped the fundamental scientific research being currently the basis for the development of search format in this regard.

Particular attention should be paid to the forefront studies [9]-[11] in the research cases. The matter is that their findings first highlighted the problems of assessment and analysis of energy characteristics of consumers as a subject of the current control of their EE consumption. In this vein, energy characteristics of using EE equipment were first represented as multivariate statistic associations between their current functioning modes and levels of their energy potential use.

[12]-[14] studies look like continuation of the search format. Their authors have proved dependence between the levels of EE consumption and technological parameters of a mining enterprise operation.

During different years of their activities, a number of other researchers [15], [16] made significant mark in the development of scientific and methodical activities, and analysis of aspects concerning electric supply/consumption by the domestic mining enterprises [15], [16]. Nevertheless, while assessing positively the research findings, we should mention it was carried out exclusively for coal mining enterprises, and based upon corresponding procedure of their functioning. In turn, which is logical, predecessors did not analyze the possibility to apply proper findings for the conditions of underground enterprises engaged in IORMs extraction. According to the specificity of the mineral mining, the method is (or rather should be) the personified search way.

To a great extent, the certain underdetermination of the mentioned studies has been compensated by foreign researchers. In such a way, papers [17]-[19] propose multipurpose models to control EE flows at the enterprises while changing consumer load levels depending upon the time of day. To obtain a solution, minimizing EE consumption cost, it is proposed to use electricity tariffs as the input parameters for a target function; the abovementioned is planned to achieve through the maximum shift of energy loads to the economical tariff zones. i.e. hours of the day.

Paper [20] represents point of view of its authors as for the optimal integration of EE control process taking into consideration uncertainty of energy supply to an enterprise consuming the EE. Papers [21]-[24] also concern the problem of consumer EE control taking into account changes in electric energy tariff during a day.

Nevertheless, while summing up, we mention with the appropriate level of correctness that depending upon the natural time influence, tendencies to solve the problem are deformed from a format of strictly canonical forms towards a new positive modern aspect, i.e. control of ESC complex functioning in accordance with the available options of power supply system (PSS) structures [25], [26].

It is logical in such an interpretation that efficiency of the expected decision will depend upon an algorithm format of the process control; in turn, the latter should involve all influential factors of an enterprise functioning technology and "develop" structurally multicriteria option to manage the corresponding control system.

At the same time, to assume following managerial measures, the research tactics concerning the development of the expected structure of the algorithm, achievement of suffi-

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ciently qualitative final result should take into consideration and monitor constantly the nature (namely, dynamics) of changes in EE consumption modes both by the specific users and the enterprise on the whole.

In terms of the analyzed problem, the structure of the current search is interesting from the viewpoint that recently the list of the available problems as for the development of a format of ESC control algorithm has been added by the necessity to take into consideration functioning mode of the abovementioned complex connected with the centralized PSS transition to the mixed centralized-autonomous power supply. In this context, PSS format is meant with the dispersed generation defining the necessity to control EE flows in more complex technical option.

Hence, the control process should be based upon such a control algorithm where against the current PSS structure and EE tariffs, both technological parameters of enterprise and electric energy supply/consumption of users have to be involved. Unfortunately, such strategic alternatives have not been developed yet.

Relying upon the listed arguments, following decision may seem trivial but it is really logical and really efficient in the context of the research. It is proposed to assume the necessity of actual input parameter identification as a starting point for further development of the functioning algorithm as well as for the operation mode of electric power complex.

In turn, the solution may be obtained only on the basis of a set of preventive model studies which will rely upon multifunctional model with integration of actual operation parameters of a mining enterprise in its structure and adequate functioning of electric power complex.

It is obvious that according to old methods, the available approaches to the development of the research model, based upon specific features of ECS complex of iron ore enterprises, cannot meet the modern requirements concerning computing quality; hence, new approaches are required.

As it has been mentioned, in the context of the previous results, obtained by researchers, representation of electric power complex of enterprises in the differentiated format (i.e. either electric supply or electric consumption) played its negative role.

The format prevents from gaining the expected positive result since the research object is not represented as the unified dynamic system. The approach to the analysis of processes in the abovementioned complex intended to obtain real managerial parameters for the functioning of adequate ESC control system that helps develop a research mathematical model which, in turn, will make it possible to find the final solutions to develop both algorithm and the whole control system.

In this vein, representation of the functioning mode of electric power complex as a stochastic process, involving its actual characteristics, is among the real approaches in the mathematical modelling procedure.

1.2. The research tasks

Purpose is to develop such a research format of a mathematical model to select and assess input parameters of a control algorithm distributing electric energy flows in the monitoring structure of electric energy supply/consumption by using equipment of mining enterprises engaged in underground extraction of iron ore raw materials.

To achieve the purpose, following problems have been formulated and solved:

– develop a mathematical model of electric power complex functioning: electric supply/consumption as a stochastic process to assess its specificity, and produce input parameters for the development of adequate algorithm to distribute electric power flows within the structure of the process control;

– carry out research as for the electric power complex functioning: electric supply/consumption according to the proposed methods in terms of operating iron ore mine, and obtaining results maximally approaching their practical implementation.

2. Methods

Suppose in the process of the research that in its broad sense, electric supply/consumption $W(t)$ is a stationary random procedure, i.e. mathematical expectation is constant and correlation function depends only upon the difference of arguments:

$$x = M[W(t)] = m_w = const; \quad K_w(t_1, t_2) = K_w(\tau), \qquad (1)$$

where:

$\tau = t_2 - t_1$.

Formulas (1) make it possible to take into consideration stochastic nature of changes in the EE consumption levels. Hence, to characterize the ESC parameters as a stochastic process within a correlation theory, it is required to know its average value, correlation function, and dispersion.

In this vein, one should involve that in practice, problems arise to calculate ECS per specified time interval, i.e. it is necessary to identify an integral of electric consumption level as a stochastic function:

$$Q(T) = \int_0^T W(t)\,dt, \qquad (2)$$

where:

$[0; T]$ – the specified time interval for electric consumption level assessment, hours.

Mathematical expectation of Function (2) is defined using the Formula:

$$M\left[Q(T)\right] = M\left[\int_0^T W(t)\,dt\right] = \int_0^T M\left[W(t)\right]dt = \int_0^T m_w dt = m_w \cdot T,$$

i.e. $m_q(T) = m_w \cdot T$. (3)

Taking into consideration the fact that under the sign of integral, Function (2) is steady, correlation function of Integral (2) will be recorded in the form of a double integral:

$$K_q(t_1, t_2) = \int_0^{t_1}\int_0^{t_2} K_w(t'' - t')\,dt'dt''. \qquad (4)$$

Since the expression, being to the right in Formula (4), depends separately upon the arguments rather than upon their difference, then the integral of the stationary process has no stationary characteristics. However, as a result of $W(t)$ stationarity, Formula (4) may be represented in the form of a linear combination of the identified integrals:

$$K_q(t_1, t_2) = \int_0^{t_2}(t_2 - \tau)K_w(\tau)\,d\tau + \int_0^{t_1}(t_1 - \tau)K_w(-\tau)\,d\tau - \int_0^{t_2 - t_1}(t_2 - t_1 - \tau)K_w(\tau)\,d\tau. \qquad (5)$$

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If one suppose in Formula (5) that $t_2 = t_1 = T$, then obtain for dispersion of Integral (2) an expression depending upon T parameter, and showing non-stationarity of the integral of a stationary function:

$$D\left[Q(T)\right] = 2\int_0^T (T-\tau)\cdot K_w(\tau)d\tau , \quad (6)$$

and taking into consideration (6), the standard deviation will be defined through the Formula:

$$\sigma\left[Q(T)\right] = \sqrt{2}\cdot\sqrt{\int_0^T (T-\tau)K_w(\tau)d\tau} . \quad (7)$$

As it has been abovementioned, ESC analysis as a stochastic process helps solve a problem of "peaks", i.e. crossing the specified level by a random function. Among other things, it helps define the average period during which electric consumption will exceed the specified one as a result of influence by random factors [27]-[29]. It is understood that such the increased electric consumption affects negatively economic performance of the enterprise.

If a stationary stochastic process is considered then average run duration has a visual value [30]. In the context of stationary process, dispersion density of electric consumption as well as distribution density of values and rate of electric consumption power does not depend upon time. Hence, formulas for mean period, during which the stationary random function is higher than the specified $w = w_0$ level for T time, average peak number during the time interval, and average run length will look like:

$$\bar{t}_{w_0} = T\int_{w_0}^{\infty} f_1(x)dx ; \quad (8)$$

$$\bar{n}_{w_0} = T\int_0^{\infty} v\cdot f_2(w_0,v)dv ; \quad (9)$$

$$\bar{\tau} = \frac{T\int_{w_0}^{\infty} f_1(x)dx}{T\int_0^{\infty} v\cdot f_2(w_0,v)dv} , \quad (10)$$

where:

$f_1(w)$ – distribution density of electric consumption level values;

$f_1(w, v)$ – two-dimensional distribution density of electric consumption level values, and rate of changes in electric consumption power.

It is expedient to introduce an idea of average peak number per unit time for the stationary process:

$$\bar{v}_{w_0} = \int_0^{\infty} v\cdot f_2(w_0,v)dv , \quad (11)$$

being equal to a peak probability per unit time.

Moreover, if electric consumption level $W(t)$ is a normal random function then Integral (2) will also be a normal process which can be characterized completely through its mathematical expectation (3) and standard deviation (7).

In the context of the normal stationary electric consumption process, the distribution law of a random function is expressed using mathematical expectation m_w and its dispersion $\sigma_w^2 = K_w(0)$ since:

$$f_1(w) = \frac{1}{\sigma_w\sqrt{2\pi}}e^{\frac{(w-m_w)^2}{2\cdot\sigma_w^2}} . \quad (12)$$

Rate of changes in electric consumption levels and their values are independent random quantities for the normal random process. Consequently, the two-dimensional distribution density of values and changes in electric consumption levels is divided into a product of normal densities of values, and rate of changes in the electric consumption process:

$$f_2(w,v) = \frac{1}{\sigma_w\sqrt{2\pi}}e^{\frac{(w-m_w)^2}{2\cdot\sigma_w^2}} , \frac{1}{\sigma_v\sqrt{2\pi}}e^{-\frac{v^2}{2\cdot\sigma_v^2}} . \quad (13)$$

Dispersion of the change rate m_w is equal to a correlation function value of zero electric consumption, i.e.:

$$\sigma_v^2 = -\frac{d^2}{d\tau^2}K_w(0) , \quad (14)$$

and mathematical expectation, resulting from stationarity of the random process, is equal to zero:

$$M\left[V(t)\right] = m_v = 0 .$$

Taking into Consideration (12) and relying upon Formula (8) derive gradually a formula for average time of the normal stationary random function staying higher than the specified time $w = w_0$ during T time:

$$\bar{t}_{w_0} = \frac{T}{\sigma_w\sqrt{2\pi}}\int_{w_0}^{\infty} e^{-\frac{(w-m_w)^2}{2\sigma_w^2}}dw = \left| \begin{matrix} t = \frac{w-m_w}{\sigma_w} & dw = \sigma_w dt \\ w = w_0 \Rightarrow t = \frac{w-m_w}{\sigma_w} & w = \infty \Rightarrow t = \infty \end{matrix} \right| = \frac{T}{\sqrt{2\pi}} = \int_{\frac{w-m_w}{\sigma_w}}^{\infty} e^{-\frac{t^2}{2}}dt = -\frac{T}{\sqrt{2\pi}}\int_{\infty}^{\frac{w-m_w}{\sigma_w}} e^{-\frac{t^2}{2}}dt =$$

$$= \frac{T}{2}\left[\frac{2}{\sqrt{2\pi}}\int_0^{\infty} e^{-\frac{t^2}{2}}dt - \frac{2}{\sqrt{2\pi}}\int_0^{\frac{w_0-m_w}{\sigma_w}} e^{-\frac{t^2}{2}}dt\right] = \frac{T}{2}\left[1-\Phi\left(\frac{w_0-m_w}{\sigma_w}\right)\right];$$

$$\bar{t}_{w_0} = \frac{T}{2}\left[1-\Phi\left(\frac{w_0-m_w}{\sigma_w}\right)\right] , \quad (15)$$

where:

$\Phi(x) = \frac{2}{\sqrt{2\pi}}\int_0^x e^{\frac{t^2}{2}}dt$ – integral Laplace function.

Further, apply Formula (9) to define average number of runs of the normal stationary random function being higher than the specified $w = w_0$ level during T time:

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$$\bar{n}_{w_0} = \frac{T}{\sigma_w\sqrt{2\pi}} e^{-\frac{(w_0-m_w)^2}{2\cdot\sigma_w^2}} \int_0^\infty v\cdot\frac{1}{\sigma_v\sqrt{2\pi}} e^{-\frac{v^2}{2\cdot\sigma_v^2}} dv = \left| \begin{matrix} t = \dfrac{v^2}{2\cdot\sigma_v^2} & vdv = \sigma_v^2 dv \\ v = 0 \Rightarrow t = 0 & v = \infty \Rightarrow t = \infty \end{matrix} \right| =$$

$$= \frac{T}{\sigma_w\sqrt{2\pi}} e^{-\frac{(w_0-m_w)^2}{2\cdot\sigma_w^2}} \int_0^\infty \frac{\sigma_v}{\sqrt{2\pi}} e^{-t} dt = \frac{T\sigma_v}{2\pi\sigma_w} e^{-\frac{(w_0-m_w)^2}{2\cdot\sigma_w^2}} \int_0^\infty e^{-t} dt;$$

$$\bar{n}_{w_0} = \frac{T\sigma_v}{2\pi\sigma_w} e^{-\frac{(w_0-m_w)^2}{2\cdot\sigma_w^2}}. \quad (16)$$

In turn, according to (15) and (16), formula for the mean run duration of the normal stationary random function, exceeding the specified $w = w_0$ level, will take the form:

$$\bar{\tau} = \frac{\bar{t}_{w_0}}{\bar{n}_{w_0}} = \frac{\frac{T}{2}\left[1 - \Phi\left(\frac{w_0 - m_w}{\sigma_w}\right)\right]}{\frac{T\sigma_v}{2\pi\sigma_w} e^{-\frac{(w_0-m_w)^2}{2\cdot\sigma_w^2}}} = \quad (17)$$

$$= \frac{\pi\cdot\sigma_w}{\sigma_v} e^{\frac{(w_0-m_w)^2}{2\cdot\sigma_w^2}} \left[1 - \Phi\left(\frac{w_0 - m_w}{\sigma_w}\right)\right].$$

(13) substitution for (11) gives a formula for an average run number per unit time:

$$\bar{v}_{w_0} = \frac{\sigma_v}{2\pi\sigma_w} e^{-\frac{(w_0-m_w)^2}{2\cdot\sigma_w^2}}. \quad (18)$$

The obtained results help involve stochastic nature of electric consumption process during the specified time interval within the electric supply/consumption complex.

While making the obtained formulas more helpful, it seems expedient to represent them in dimensionless form using similarity theory and dimensional analysis [29], [30]. Such an approach makes it possible to transform variables into multiplicative complexes through reducing the number of independent variables, which helps simplify the study. In the dimensionless form, (15)-(18) Formulas look like:

$$\hat{\bar{t}}_{\hat{w}_0} = 1 - \Phi(\hat{w}_0 - \hat{m}_w); \quad (15')$$

$$\hat{\bar{n}}_{\hat{w}_0} = \hat{\sigma}_v e^{-\frac{(\hat{w}_0-\hat{m}_w)^2}{2}}; \quad (16')$$

$$\bar{\tau}_{\hat{w}_0} = \frac{\pi}{\hat{\sigma}_v} e^{\frac{(\hat{w}_0-\hat{m}_w)^2}{2}} \left[1 - \Phi(\hat{w}_0 - \hat{m}_w)\right]; \quad (17')$$

$$\bar{v}_{\hat{w}_0} = \frac{1}{2\pi\hat{\sigma}_w} e^{-\frac{(\hat{w}_0-\hat{m}_w)^2}{2}}, \quad (18')$$

where:

$$\hat{\bar{t}}_{\hat{w}_0} = \frac{2\cdot\bar{t}_{w_0}}{T};\ \hat{m}_w = \frac{m_w}{\sigma_w};\ \hat{w}_0 = \frac{w_0}{\sigma_w}; \quad (19)$$
$$\hat{\bar{n}}_{\hat{w}_0} = \frac{\bar{n}_{w_0}\cdot 2\pi}{T};\ \hat{\sigma}_v = \frac{\sigma_v}{\sigma_w}.$$

Analysis of the formulas shows that the variables are represented in their multiplicative form, i.e. in the form of division and product. In addition, number of the variables decreased from five down to three, which simplifies the analysis significantly. Back transition from the dimensionless shape to the dimensional one takes place using the Formulas (19):

$$\bar{t}_{w_0} = \frac{T}{2}\hat{\bar{t}}_{\hat{w}_0};\ m_w = \sigma_w\cdot\hat{m}_w;\ w_0 = \sigma_w\cdot\hat{w}_0;\ \bar{n}_{w_0} = \frac{T}{2\pi}\hat{\bar{n}}_{\hat{w}_0}; \quad (20)$$
$$\sigma_v = \sigma_w\cdot\hat{\sigma}_v;\ \bar{\tau}_{w_0} = \bar{\tau}_{\hat{w}_0};\ \bar{v}_{w_0} = \bar{v}_{\hat{w}_0}.$$

The findings help take into consideration stochastic nature of electric supply/consumption process per specified time interval. It is especially important that "peaks" are involved both qualitatively and with their parametric calculation to be particularly useful if the methods are implemented in practice.

3. Results and discussion

Consider the modelling of electric supply/consumption process as a stochastic procedure in terms of Kryvorizka mine. Figure 1 shows levels of EE consumption during fifty hours.

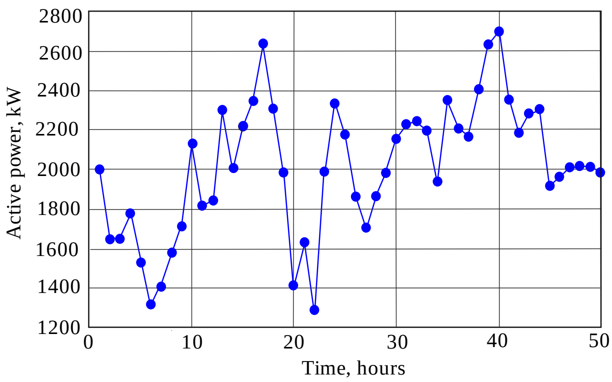

Figure 1. Hourly dynamics of changes in electric consumption in Kryvorizka mine

Analysis of the graph, represented in Figure 1, explains that the electric energy consumption levels are characterized by a stochastic process. Average power of electricity consumption per the specified interval (i.e. fifty hours) is:

$$\bar{w} = \frac{1}{50}\sum_{i=1}^{50} w_i = 2017. \quad (21)$$

In turn, dispersion is:

$$D[W] = \frac{1}{49}\sum_{i=1}^{50}(w_i - \bar{w})^2 = 110596.5. \quad (22)$$

Correlation function of electric consumption levels is identified through the formula:

$$K_w(l) = \frac{1}{50 - l + 1}\sum_{j=0}^{50-l}(w_j - \bar{w})(w_{j+1} - \bar{w}), \quad (23)$$
$$(l = 0, 1, ..., 4).$$

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Figure 2 demonstrates graphs of the standardized correlation function calculated on the formula:

$$\tilde{K}_w(l) = \frac{K_w(l)}{D[W]}, \tag{24}$$

and the function approximation using the formula:

$$\tilde{K}_w^a(\tau) = e^{-\alpha\cdot|\tau|}\left(1+\alpha\cdot|\tau|\right). \tag{25}$$

The least-squares method, applied to ordinates of the statistically normalized correlation Function (23), has helped identify a parameter value in Formula (25) being:

$$\alpha = 1.4. \tag{26}$$

As a result, Formula (25) takes the form:

$$\tilde{K}_w^a(\tau) = e^{-1.4\cdot|\tau|}\left(1+1.4\cdot|\tau|\right). \tag{27}$$

Analysis of graph arrangement in Figure 2 shows rather sufficient their approach.

To support the conclusion, determination index has been calculated through the formula:

$$R^2 = 1 - \frac{S_a^2}{D\left[\tilde{K}_w\right]}, \tag{28}$$

where:

$$S_a^2 = \frac{1}{4}\sum_{l=0}^{4}\left(\tilde{K}_w(l) - e^{-1.4 l}\left(1+1.4\cdot l\right)\right).$$

Calculation on Formula (27) involving numerical results has derived the value:

$$R^2 = 1 - \frac{0.00108}{0.1731} = 0.994. \tag{29}$$

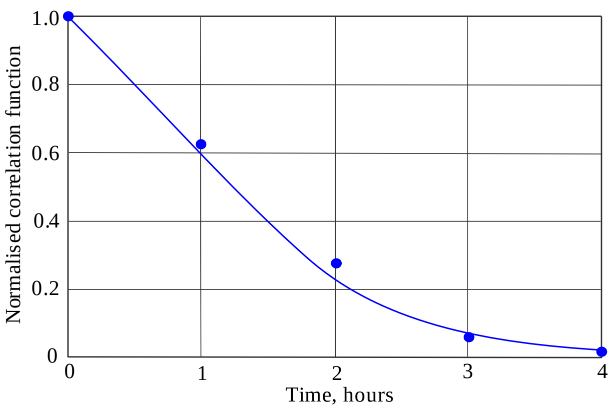

Figure 2. Statistically normalized correlation Function (22) and its approximation according to Formula (25)

The determination index value (29) makes it possible to suggest that according to a Chaddock scale the analyzed case demonstrates rather strong correlation between variables [29], [30].

Study of statistical material as for EE consumption levels in Kryvorizka mine has shown that the normal stationary stochastic process takes place which parameters are identified with the help of Formulas (19) and (20). As a result, the formula of distribution density of EE consumption levels will be recorded as follows:

$$f_1(w) = \frac{1}{332.56\sqrt{2\pi}} e^{\frac{(w-2017)^2}{2\cdot 110596.5}}. \tag{30}$$

Hence, the abovementioned calculation formulas can be used. Taking into Consideration (20) and (25), the formula to calculate correlation formula of the EE consumption levels is:

$$K_w(\tau) = 110596.5\cdot e^{-1.4\cdot|\tau|}\left(1+1.4\cdot|\tau|\right). \tag{31}$$

Consequently, dispersion of changes in the EE consumption levels is calculated in such a way:

$$\sigma_v^2 = -\frac{d^2}{d\tau^2}K_w(0) = \sigma_w^2\cdot\alpha^2. \tag{32}$$

Taking into numerical values (20) and (24), we will have:

$$\sigma_v^2 = 110596.5\cdot 1.4^2 = 216769.1. \tag{33}$$

To identify average time when the EE consumption levels are higher than the specified level, apply Formula (15′) involving (21) and (22):

$$\hat{\bar{t}}_{\hat{w}_0} = 1 - \Phi\left(\hat{w}_0 - 6.1\right). \tag{34}$$

Figure 3 demonstrates a dependence graph of the dimensionless average time of the EE consumption level being higher than the specified dimensionless level (34). The graph analysis shows that while being in the dimensionless form during the EE consumption level increase, the average time of electric consumption power, exceeding the level, decreases.

Apply Formulas (20) to transit to dimensional values. Let:

$$\hat{w}_0 = 6.6, \tag{35}$$

then the following takes place according to Function (34) and graph in Figure 3:

$$\hat{\bar{t}}_{\hat{w}_0} = 0.62. \tag{36}$$

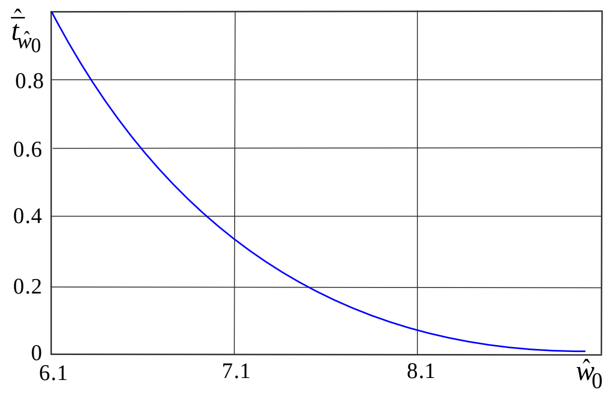

Figure 3. Dimensionless average time dependencies when the EE consumption level exceeds the specified $\hat{\bar{t}}_{\hat{w}_0}$ quantity

If we assume that the observation period is $T = 24$ hours and $\sigma_w = 332.56$ kW then average time of the EE consumption levels staying higher than $w_0 = 2195$ kW during a day will be $\bar{t}_{2195} = 12\cdot 0.62 = 7.44$ hours.

To define the mean number of electric consumption peaks, apply formula (16′); according to (21), it takes the form:

$$\hat{\bar{n}}_{\hat{w}_0} = \hat{\sigma}_v e^{-\frac{(\hat{w}_0-6.1)^2}{2}}. \tag{37}$$

Figure 4 represents graphs of Function (37). Standard deviation of changes in the rates of EE consumption has been selected as the parameter. Analysis of graphs, shown in Figure 4, explains that if the specified EE consumption

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power level increases, the average number of peaks decreases; nevertheless, increase in the standard rate deviation of the power, the average peak number also increases.

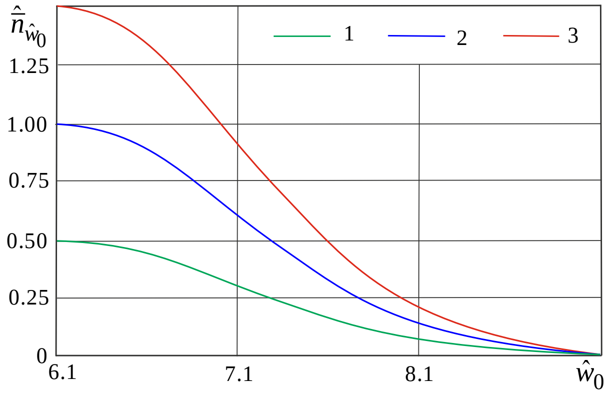

Figure 4. Dimensionless dependencies of the average peak number exceeding the specified level of electricity consumption: 1 – $\hat{\sigma}_v = 0.5$***; 2 –*** $\hat{\sigma}_v = 1$***; 3 –*** $\hat{\sigma}_v = 1.5$

If we assume that the observation period is $T = 24$ hours, and $\sigma_w = 332.56$ kW and $\sigma_v = 465.6$ kW/h then the average peak number during the period is higher than the specified electricity consumption level $w_0 = 2195$ kW will be $\bar{n}_{2195} = \frac{24}{2\pi} 0.8825 = 3.37 \approx 3$.

In turn, to identify the average peak interval, use Formula (17′); according to (21), it takes the form:

$$\bar{\tau}_{\hat{w}_0} = \frac{\pi}{\hat{\sigma}_v} e^{\frac{(\hat{w}_0 - 6.1)^2}{2}} \left[1 - \Phi\left(\hat{w}_0 - 6.1\right)\right]. \quad (38)$$

Figure 5 demonstrates dimensionless dependence graphs of the average peak interval, exceeding the specified electric consumption power in accordance with Formula (38). Analysis of the graphs shows that increase in the specified value of electric consumption power, the mean peak interval, exceeding the predetermined level, decreases. In addition, when the standard rate deviation of changes in electric power consumption increases as a parameter, the average peak intervals decrease.

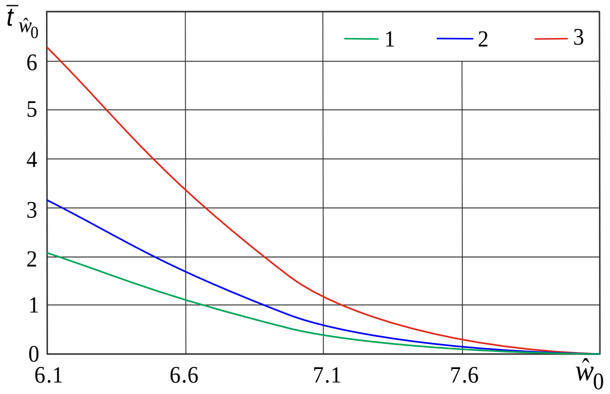

Figure 5. Dimensionless dependencies of the average peak numbers, exceeding the specified level of electric consumption power: 1 – $\hat{\sigma}_v = 0.5$***; 2 –*** $\hat{\sigma}_v = 1$***; 3 –*** $\hat{\sigma}_v = 1.5$

If we assume that the observation period is $T = 24$ hours, and $\sigma_w = 332.56$ kW and $\sigma_v = 465.6$ kW/h then the average peak number during a day, exceeding the specified electric consumption level $w_0 = 2195$ kW will be $\bar{\tau}_{2195} = 1.71$ hours.

Consequently, according to the research logic, consider electric consumption per specified period relying upon Formulas (3) and (6). Taking into Consideration (21), we have:

$$m_q(T) = m_w \cdot T = 2017 \cdot T \text{ kW/h}. \quad (39)$$

In turn,

$$D\left[Q(T)\right] = 2\sigma_w^2 \int_0^T (T - \tau) \cdot e^{-\alpha \cdot \tau} (1 + \alpha \cdot \tau) d\tau =$$

$$= \frac{2\sigma_w^2}{\alpha^2}\left[3\left(e^{-\alpha \cdot T} - 1\right) + \alpha T \left(2 + e^{-\alpha \cdot T}\right)\right].$$

According to (22) and (31), we have:

$$D\left[Q(T)\right] = 1.1285 \cdot 10^5 \left[3\left(e^{-1.4T} - 1\right) + 1.4T\left(2 + e^{-1.4T}\right)\right],$$

or

$$\sigma\left[Q(T)\right] = 335.93 \cdot \sqrt{3\left(e^{-1.4T} - 1\right) + 1.4 \cdot T \cdot \left(2 + e^{-1.4T}\right)}. \quad (40)$$

Figure 6 demonstrates electric consumption graphs in accordance with Formula (38) taking into consideration the standard intraday deviation (39).

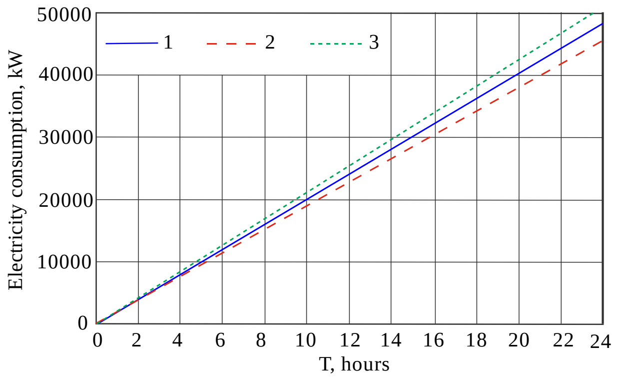

Figure 6. Intraday electric consumption levels: 1 – average; 2 – that one decreased by the standard deviation (39); 3 – that one increased by the standard deviation (39)

Analysis of the graphs in Figure 6 shows that time increase results in the mean electric consumption increase. Along with it, deviation of EE consumption from the average level increases linearly at the expense of the standard deviation (39) achieving its maximum for the final day time.

If the specified period is $T = 24$ hours then according to (38), and (39) we have $m_q(24) = m_w \cdot 24 = 2017 \cdot 24 = 4.8408 \cdot 10^4$ kW/h and $\sigma[Q(24)] = 2692$ kW/h.

Hence, the derived formulas help analyze electric consumption modes as the normal stochastic process within the correlation theory. Studies of ESC as a stochastic process have made it possible to build a mathematical model while using actual statistical material in terms of Kryvorizka mine.

The synthesized model intended to develop architecture of ESC control algorithm has identified such stochastic characteristics of electric consumption as average ones and dispersions; the mean period of electric consumption level (considered as a stationary random function) being higher than the specified $w = w_0$ level during T time; average peak number per the interval; and average period of the peak.

Innovativeness of the research is as follows. Under the real conditions of EE consumption, ways to solve a problem of

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selection and assessment of electric supply/consumption for iron ore mines have been identified taking into consideration its stochasticity to develop the automated control system.

The identified parameters are input constants required to control a process of electric supply/consumption by iron ore enterprises engaged in underground IORMs mining.

4. Conclusions

Mathematical modelling of electric consumption, being a part of electric supply/consumption as a stochastic process, has made it possible to identify its deeper characteristics connected with the process randomness. The available techniques, assessing parameters of electric supply/consumption level relying exceptionally on the average values, were supplemented by new parameters characterizing their dispersion and proposing new adequacy level relative to the real ones. The research, basing upon statistical material as for the EE consumption levels and deriving from the technological data of operating mine, has proved availability of the normal stationary stochastic process which parameters are defined through the obtained analytical ratios. As a result, calculation formula has been developed concerning distribution density of the EE consumption levels.

The visual and analytical analysis of the obtained modelling results has made it possible to identify such stochastic characteristics of electric supply/consumption as average ones and dispersions; the mean period of electric consumption level (considered as a stationary random function) being higher than the specified $w = w_0$ level during T time; average peak number per interval; and average period of the peak. The findings are the basis for methods to assess input parameters to develop the automated control system; moreover, the results are characterized by their originality. Application practice of the developed methods has proved its efficiency, which can be considered as the reason to recommend it to be implemented in the relevant research projects.

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Модельні дослідження з ідентифікації вхідних параметрів алгоритму керування процесом електропостачання-електроспоживання підземних залізорудних підприємств

О. Сінчук, Р. Стжелецкі, Т. Берідзе, І. Пересунько, Д. Кобеляцький, В. Запальський

Мета. Розробка дослідницького формату математичної моделі для вибору та оцінювання вхідних параметрів алгоритму керування розподілом електроенергопотоків у структурі управління процесом електропостачання-енергоспоживання приймачами гірничорудних підприємств з підземними способами видобутку залізорудної сировини.

Методика. Платформа наукового пошуку базувалась на системності в означені об'єкта пошуку. Процес аналітичних досліджень проводився з застосуванням теорії випадкових процесів, котрі були адаптовані до реальних умов з залученням для цього результатів експериментальних замірів в умовах діючих залізорудних підприємств з підземними способами видобутку залізорудної сировини. При розбудові логістики досліджень прийнято як факт, що процес: електропостачання-електроспоживання, аналізуємих видів гірничих підприємств, являє собою стохастичну функцію, оскільки в кожний поточний момент часу формується під впливом ряду наперед невідомих складових. Застосування методів випадкових функцій, зокрема елементів кореляційної теорії, дозволило визначити основні вхідні та вихідні параметри, які в достатньому обсязі характеризують електропостачання-електроспоживання як стохастичний процес для розбудови алгоритму керування цим процесом.

Результати. Розроблена математична модель комплексу: електропостачання-електроспоживання як стохастичного процесу з метою оцінювання його особливостей та рівнів впливу на економічні показники функціонування електроенергетичної системи підземних гірничорудних підприємств. При формування алгоритму керування процесом розподілу електроенергопотоків між споживачами аналізуємих видів залізорудних підприємств враховувались стохастичність функціонування вищезгаданого комплексу.

Наукова новизна. Досліджено процес електропостачання-електроспоживання споживачів електроенергії підземних залізорудних підприємств в форматі стохастичного процесу їх функціонування. Вперше побудовано синтезовану математичну модель, визначені стохастичні характеристики потужності електроспоживання як середні так і дисперсні; середній час рівнів споживання електричної енергії як стаціонарної випадкової функції протягом відповідного часу; середня кількість сплесків рівнів електроспоживання за цей проміжок часу та середня тривалість їх викидів. Дослідження процесу електропостачання-електроспоживання як стохастичного процесу дозволило вирішити "сплесків" на режими споживання електричної енергії приймачами даних підприємств, тобто про перетин випадковою функцією заданого рівня електростпоживання. Це дозволило визначити середній час, протягом якого рівень споживання електричної енергії буде перевищувати заданий рівень внаслідок впливу на цей процес випадкових факторів.

Практична значимість. Обчислення параметрів функціонування комплексу електропостачання-електроспоживання, що застосовуються в даний час, згідно існуючих обчислюючих форматів, мають недостатню точність, оскільки розрахунки проводяться за середніми величинами, не враховуючи стохастичність цього процесу, що характерно для аналізуємих гірничих підприємств. Це обмежує можливості розбудови адекватної системи керування електроенергетичним процесом в даних видах гірничих підприємств зі специфікою технології їх функціонування. Розроблена методика динаміки функціонування електропостачання-електроспоживання як стохастичного процесу дозволяє поширити її застосування при формуванні та прийнятті ефективних управлінських рішень в аналізуємому процесі. Більш того, при окремій особливості рівнів електроспоживання, яка визначається нормальним законом розподілу, можливо досяжною буде і повна характеристика процесу електропостачання-електроспоживання, та обсягів енергоспоживання за визначений час в форматі випадкових процесів.

Ключові слова: *модель, електропостачання, електроспоживання, стохастичність, оцінка, випадковий процес, гірниче підприємство*

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