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Reliability analysis of open-pit power supply system components

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Abstract
In the field of designing power supply systems of open pits an important role is attributed to the problems of components reliability analysis, which can be solved by integrated application of different analysis methods for individual types of electrical equipment and network devices in power supply systems. The purpose of the work is to establish optimal parameters for an open-pit mine power supply at mining and processing complexes, and to conduct research that allows a technical and economic model of the system to be created. It has been established that mathematical statistics provides a number of methods for establishing the homogeneity (or heterogeneity) of the population of random variable values. When analyzing the data of failure statistics of electrical equipment, the method of comparative estimate of two sample averages (compared to the method of comparing the empirical distribution with the normal distribution or the moving average method) is the most acceptable. The paper presents accident rates of electrical equipment of open-pit substations and network devices of the quarry processed on the basis of data, also presents the relationship between the reliability of the circuit and its elements and shows the influence of protection reliability on the reliability of the circuit. Methods of optimizing open-pit power supply systems are presented, which consist in the use of first-order gradient methods, second-order methods or the so-called quadratic optimization methods, and random search methods. A group of gradient methods is the most widespread for solving nonlinear programming problems, among which the method of steepest descent should be considered primarily. The combination of random search with the penalty function method makes it possible to determine conditional extrema for the problem of optimizing the electrical grid and system operation mode. The method of random descent, which consists in determining the minimum of the target function according to an appropriate algorithm, is also considered, in which the direction of motion is generally given by a random vector uniformly distributed over a hyposphere.

Keywords
reliability of components, power supply system, open pit, gradient methods, accident rate, mine substations, random search, target function

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ЭНЕРГЕТИКА, АВТОМАТИЗАЦИЯ И ЭНЕРГОЭФФЕКТИВНОСТЬ

Научная статья

Анализ надежности элементов системы электроснабжения карьеров

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Аннотация
В области проектирования систем электроснабжения карьеров важная роль отводится вопросам анализа надежности элементов, которые могут быть решены в ходе проведения комплексного применения различных методов расчета отдельных видов электрооборудования и сетевых устройств в системах электроснабжения. Целью работы является установление оптимальных параметров электроснабжения рудника открытых горных работ горно-обогатительных комбинатов, проведение исследований, позволяющих создать технико-экономическую модель системы. Установлено, что математическая статистика дает ряд методов установления однородности (или разнородности) совокупности значений случайной величины. При анализе данных аварийной статистики электрооборудования наиболее приемлемым является метод сравнительной оценки двух выборочных средних (по сравнению с методом сравнения эмпирического распределения с нормальным или методом скользящей средней). В работе приведены обработанные на основе данных аварийности электрооборудования рудничных подстанций и сетевых устройств карьера, также представлены соотношения между надежностью схемы и ее элементами и показано влияние надежности защиты на надежность схемы. Представлены методы оптимизации систем электроснабжения карьеров, заключающиеся в применении градиентных методов первого порядка, методов второго порядка или так называемых квадратичных методов оптимизации, методов случайного

поиска. В качестве наиболее распространенных для решения задач нелинейного программирования используется группа градиентных методов, среди которых в первую очередь следует рассматривать метод наискорейшего спуска. Сочетание случайного поиска с методом штрафных функций дает возможность определять условные экстремумы для задачи оптимизации режима работы электрической сети и системы. Также рассматривается метод случайного спуска, заключающийся в определении минимума целевой функции по соответствующему алгоритму, при котором направление движения в общем случае задается случайным вектором, равномерно распределенным по гипосфере.

Ключевые слова

надежность элементов, система электроснабжения, карьер, градиентные методы, аварийность, рудничные подстанции, случайный поиск, целевая функция

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Introduction

Fulfillment of the problems set for the mining industry is impossible without further increase in production efficiency, labor productivity and automation of production processes, increase of the efficiency level of mining production and the use of electrical equipment [1, 2].

The growth of power availability per man leads to an increase in the cost of creating and operating a power supply system (PSS). In this regard, the problems of building an optimal PSS not only for a mining enterprise as a whole, but its individual subsystems as well, solved at the design stage, as well as the problems of building reliability models of a PSS [3, 4] are of particular relevance.

The application of optimization methods in the design practice, including those using artificial intelligence, will significantly improve the designing quality in accordance with the problems of the need to improve the design business on the basis of the wide introduction of scientific achievements into the engineering practice [5, 6].

The achieved scientific and technical progress in the technique and technology of open-pit mining (a high degree of concentration of mining operations, operation of large deep pits, steady growth of the installed capacity of mining machines and power availability per man) poses a number of technical and economic problems of efficiency improvement in the field of designing power supply of open pits, which require urgent solution.

The efficiency of open-pit PSS depends not only on the quality of the equipment used [7, 8], but also on the correctness of design decisions and the quality of design documentation. However, at present PSS's are designed by traditional methods developed for the conditions of open pits of relatively small productivity and depth. Complex interrelationships between system parameters, electrical loads and mining-geometric, technical and technological parameters of modern open pits are taken into account during designing insufficiently. Electrical loads are analyzed on the basis of demand coefficients, and the choice of the power supply scheme is based on the technical comparison of a limited number of options without taking into account the dynamics of mining operations and changes in electrical loads. This does not help to choose its optimal parameters.

When solving technical and economic problems of power supply designing, design institutes cannot widely use the capabilities of computer technology due to the lack of algorithms suitable for specific conditions of open-pit mining. It practically excludes multivariant and optimization analyses, causes deterioration of the quality and increase of terms for design preparation, with an abrupt increase in the scope of design.

The purpose of the work is to establish the optimal parameters of power supply of an open-pit mine within mining and processing complexes (MPC) and to conduct studies that allow investigation of the reliability of PSS individual components in order to further consider the safety of work in the electrical grids of the mining industry [9, 10].

Analysis of existing power supply schemes of open pit mines

The accident rate of individual components of grids and electrical equipment of enterprises depends on many disturbing factors, on the state of installation and repair works performed, various operating conditions, their technical state, etc. [11, 12]. The influence of each of these factors separately is often insignificant and practically imperceptible, but the total effect leads to results fluctuating from case to case. Consequently, accident rates can be considered as a random variable, which is the subject of mathematical statistics and probability theory. Proceeding from the statistical nature of the accident rate phenomenon and from the essence of the probability concept of some event, the quantitative expression of the reliability concept can be formulated as follows:

reliability is the probability that a component or an installation as a whole will operate satisfactorily for a certain period of time. For example, if the duration of emergency downtime of the installation during a year is equal to 8.76 hr, then the probability of its failure is $P = 8.76/8760 = 10^{-3}$, and the reliability is $P' = 1 - 10^{-3}$.

Method of reliability analysis of electrical equipment individual types and network devices

In electrical distribution networks and systems, damage to certain types of components can cause downtime of a part or the whole installation for the time of finding and eliminating the failure (emergency downtime), or for the time of finding the failure and subsequent disconnection of the damaged section (emergency shutdown time) [13, 14].

According to the operational data on the emergency downtime and emergency shutdown duration x of the main types of electrical equipment and network devices used in open pits, the two most important statistical characteristics are determined: the weighted average of argument $\bar{x}$ and standard σ_x.

Comparison of the obtained average values and standards shows that the value of coefficient of variability k for the considered variation series keeps some constant value with maximum deviation of its individual values from the average value up to 4%:

$$k = \frac{\sigma_i}{x_i}. \tag{1}$$

Respectively, the following ratio is true practically for all sample distributions:

$$\sigma_i = k\bar{x}_i. \tag{2}$$

The obtained ratio indicates the same regularity in distribution of all considered variation series and that we should expect almost a constant value of the standard of the modifying function argument for all sample distributions.

To reveal the law of distribution of the observed frequencies for the emergency downtime and emergency shutdown time, a quantile plot of the argument distribution for some types of electrical equipment is drawn on the probability paper (Fig. 1).

As the quantile plot shows, the points of values of some distribution functions are grouped near curves resembling a logarithmic curve.

Fig. 2 shows new quantile plots on the log-probability paper. The plot shows that the points are grouped very closely near straight lines, with more or less noticeable deviation of the points from a straight line observed for only up to 5% and above 95% of the quantiles.

For graphic estimation of the obtained deviations of the distribution function values from a straight line (Fig. 3), the curves of permissible values of emergency deviations from the theoretical line with the reliability (probability) of $P = 0.95$ were drawn.

Fig. 3 shows that the permissible value of random deviations from the theoretical line is much higher at values P close to 0 or 100% than at the values close to 50%. Therefore, the observed noticeable deviation of points of the distribution function values from a straight line of up to 5% and above 95% quantiles (see Fig. 2) cannot noticeably change the sample distribution law. In addition, the number of observations within these limits does not exceed 10% of the sample volume. Comparison of the curves for permissible values of random deviations from the theoretical line with the obtained deviations of the values of the sample distribution function from a straight line shows that the latter are within the permissible limits of random deviations at $P = 0.95$ and $n > 250$. Respectively, the emergency downtime and emergency shutdown

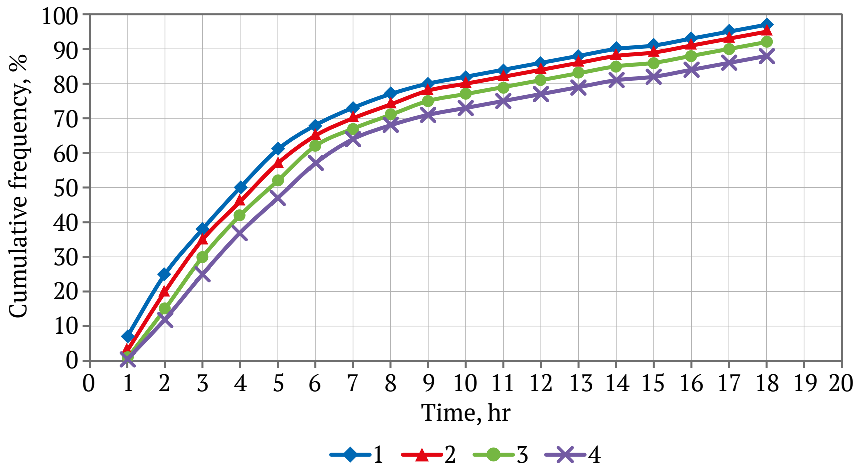

Fig. 1. Quantile plot of distribution of the emergency downtime and emergency shutdown time of open pit excavator cables and networks

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time both in case of damaged excavator cables and in case of open-pit network failures is distributed according to the log-normal distribution. According to the result of graphical analysis, sample distributions are adjusted by the equation:

$$\Phi(u) = \frac{1}{\sigma_u\sqrt{2\pi}} e^{-\frac{(u_i-\bar{u})^2}{2\sigma_u^2}}, \qquad (3)$$

where $\Phi(u)$ is the distribution function; u_i is the argument of the modifying function; $\bar{u}$ is the mean value of the modified argument; and σ_u is the standard of the modified argument.

The results of analytical evaluation of the discrepancy between sample and theoretical frequencies are: $\lambda_1 = 0.307$ and $P_1 = 0.999$; $\lambda_2 = 0.818$ and $P_2 = 0.52$; $\lambda_3 = 0.448$ and $P_3 = 0.987$; $\lambda_4 = 0.942$ and $P_4 = 0.365$ (indexes P and λ correspond to line numbers given in Figs 1, 2). Random values λ, which are greater than or equal to the observed values, may occur with a probability greater than 0.365, i.e., the difference between the theoretical and sample distributions is insignificant. Analytical verification confirms the conclusions obtained by graphical analysis.

The slope of a straight line to the quantile plot abscissa axis in case of log-normal distribution is determined by the value of the modifying function argument standard.

The quantile plot (see Fig. 2) shows that the value of the modifying argument standard for all distributions is very stable, since all the straight lines of the plot are within two straight lines insignificantly distant from each other.

The average value of the modifying argument standard for all the distributions under study is $\sigma_u = 0.347$. The maximum deviation of its individual values from the average value is 20.1%, which can be neglected and in the first approximation $\sigma_u = 0.347$ = const can be assumed ($\sigma_u = \lg u_{60} - \lg u_{15.9}$, where u_{60} and $u_{15.9}$ are 60% and 15.69% of quantiles respectively).

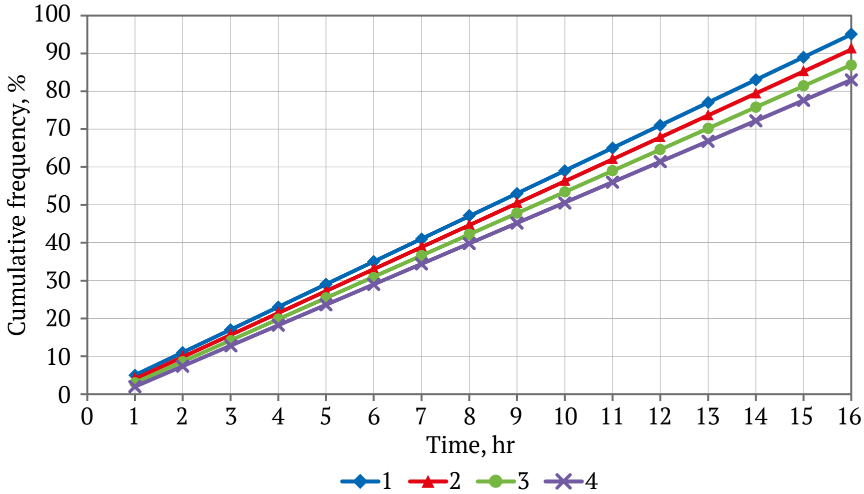

Fig. 2. New quantile plot of distribution of the emergency downtime and emergency shutdown time of open pit excavator cables and networks

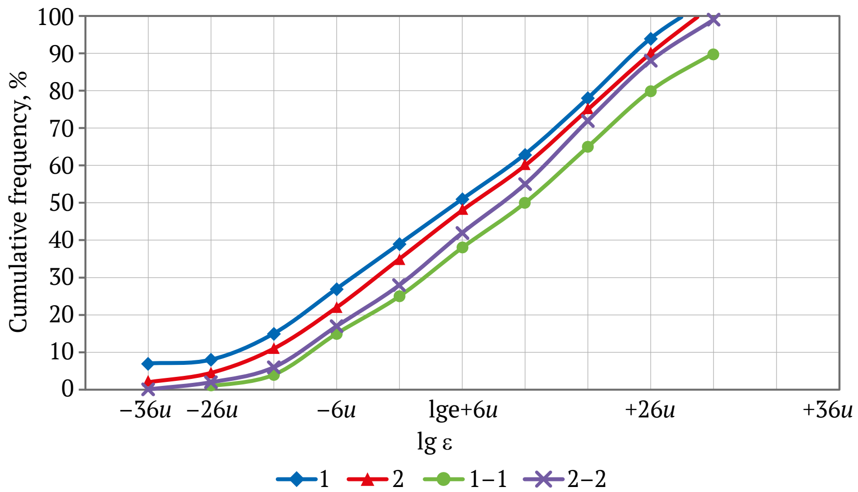

Fig. 3. Curves of permissible random deviations from the theoretical line with the reliability of $P = 0.95$, 1–1 at $n = 100$, 2–2 at $n > 250$

Similar analyses made for all main components of open-pit power supply schemes show that:

1. The emergency downtime and emergency shutdown time is subject to the log-normal distribution.

2. The modifying function argument standard practically maintains a constant value.

When the distribution is log-normal, the following ratio takes place:

$$M(\lg u) = \lg \varepsilon, \tag{4}$$

where $M(\lg u)$ is the mathematical expectation of the logarithm of the observed argument; $\lg \varepsilon$ is the mean value of the modified argument.

The value of $\lg \varepsilon$ is median Me in the modified argument distribution, and the quantiles of the modified value coincide with the modified quantiles of the original value, as long as the modification is performed by a non-decreasing function. Hence, value ε shall be equal to the median in the x distribution. However, the median changes if any values of the argument less than the median change randomly, remaining less than Me under these changes. This property of the median and the fact that the probabilities of occurrence of a certain number of observations to the left and right of the median are equal to each other, allow them to be used to determine the mean values of the argument with relatively small sample sizes.

Based on the known ratio:

$$\lg \bar{x} = \lg \varepsilon + 1.151\sigma_u^2 \tag{5}$$

the following can be written:

$$\lg \bar{x} = \lg \varepsilon + 0.1387. \tag{6}$$

The obtained equality can be used to determine the average value of the considered failure parameters and to make practically its exact estimate with very insignificant sample sizes, even with n = 25–25. At the same time, the obtained mean values are within the confidence limits defined by the accuracy of 0.15 of the mean value determined with the sample sizes exceeding 150–200 and having a reliability practically equal to 0.9. Mean values determined with such accuracy and reliability are quite applicable as input data for determining the quantitative indicators of the electrical grid reliability.

The conducted analyses show that the annual durations of emergency downtime of open-pit electrical equipment are also distributed according to the log-normal distribution and the values of the modified argument standard have deviations not exceeding 20% of the determined standard mean value of σ_u = 0.347. Respectively, the time of emergency downtime of certain types of electrical equipment and network devices per year can also be calculated by the proposed method without determining their average damage rate per year with subsequent multiplication by the average duration of emergency downtime.

To determine the reliability index of power supply schemes, it is necessary to know the third failure parameter – the mean value of the number of failures per year of individual types of electrical equipment and network devices.

Determination of the arithmetic mean of the number of failures is not difficult, but determination of the statistical mean necessary to calculate the quantitative reliability indicators is associated with some difficulties (complications) related to the need to take into account the degree of influence of disturbing factors on the failure parameter values.

Individual values of failure parameters, possessing a common mean level, deviations from which appear to be random, constitute a homogeneous population. In this case, the value of their arithmetic mean is the mean in the statistical sense and, expressing the mean level, summarizes random deviations. If a part of their disturbing factors causes a systematic deviation of the values of failure parameters from some level, along with random values, it creates a new level (mean), thus forming a heterogeneous population. The arithmetic mean loses its cognitive meaning when one tries to use it to characterize failure parameter values that make up a heterogeneous population. This is because it is impossible to express the mean level that does not exist in a heterogeneous population by any indicator. In this case, to obtain a statistical mean, it is necessary to divide the heterogeneous population into homogeneous ones and then to determine the mean value for each homogeneous population of failure parameters and, if necessary, to establish the form and measure of correlation between the failure parameter values and disturbing factors.

Mathematical statistics provides a number of methods for establishing the homogeneity (or heterogeneity) of the population of random variable values. When analyzing the data of failure statistics of electrical equipment, the method of comparative estimate of two sample averages compared to the method of comparing the empirical distribution with the normal distribution or the moving average method is the most acceptable

The essence of the recommended method as applicable to the failure data processing is that the sample data for a certain set of disturbing factors determines the value of $\bar{x}_1$. After excluding the factors whose influence on the formation of the average level is clarified from the factors population, a new sample is taken and average $\bar{x}_2$ is also determined. Then the criterion is determined:

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\dfrac{(n_1+n_2)\left[\sum(x_1-\bar{x}_1)^2+\sum(x_2-\bar{x}_2)^2\right]}{n_1 n_2(n_1+n_2-2)}}}. \quad (7)$$

According to the value of t found and the number of degrees of freedom k, probability P is found using the Student's distribution probabilities table. It can be used to expect value t to be numerically equal to or greater than the observed (calculated) value. If $P > 0.95$, the compared averages differ insignificantly and the values of the failure parameters form a homogeneous population. The number of degrees of freedom is determined as the number of independent values of failure parameters. If for some sample of size n_1 the values of failure parameters shall satisfy h conditions linking them, then the number of degrees of freedom is equal to: $k = n_1 - h$.

Accident rates

Accident rates of electrical equipment of open-pit substations and network devices [15, 16], processed on the basis, given in Table 1.

Correlations between reliability of the scheme and its components

Using the provisions of the probability theory and the data given in Table 1, correlations between reliability of the scheme, its individual circuits and components with different connection types were obtained:

– with series connection a failure of each component causes a malfunction of the whole installation and therefore: $P' = 1 - \Sigma p_i$, $P'' = \Sigma p_i$;

– with parallel connection, power outage can occur only if all parallel circuits fail, therefore: $P' = 1 - p_1p_2$, $P'' = p_1p_2$;

– with mixed connection:

$$P' = (1 - p_1p_2)\cdot(1 - p_3),\ P'' = p_1p_2 + p_3,$$

where p_i is the probability of failures of the scheme individual parallel circuit components; p_1, p_2 is the probability of failures of individual parallel circuits and components; p_3 is the probability of failures of a series circuit or component in case of mixed connection; P', P'' are the reliability and probability of failure of the scheme.

In conclusions of accident rates of individual components and circuits the schemes are considered as events independent of each other.

Influence of protection reliability on scheme reliability

Based on the essence of the probability concept of some event to determine the probability of incorrect action of protection p_3, it is necessary to take a certain number of protection actuations S for the number of all cases belonging to some particular stochastic test plan, and to take the statistical mean of the number of malfunctions of protection m with the accepted number of actuations for the number of cases favorable to the protection malfunction, i.e.:

$$p_3 = mS. \quad (8)$$

Downtime duration of the busbar system T for incorrect protection functions p_3 can be determined from the expression:

Table 1

Accident rates of electrical equipment of open-pit substations and network devices

Item No.	Name of electrical equipment and network devices	Number of damages per 1 facility, times/year	Probability of emergency shutdown	Probability of emergency downtime
1	Flexible cables	3.65	$0.595\cdot10^{-4}$	$13.1\cdot10^{-4}$
2	In-pit overhead power lines with excavator number x used for – stripping – offsite dumps – onsite dumps	 $y=4.7\cdot x+1.7$ $y=1.32\cdot x+0.87$ $y=2.5\cdot x+0.67$	 $0.595\cdot10^{-4}$ $0.595\cdot10^{-4}$ $0.595\cdot10^{-4}$	 $13.5\cdot10^{-4}$ $4.6\cdot10^{-4}$ $6.66\cdot10^{-4}$
3	Mobile substations	0.99	$0.595\cdot10^{-4}$	$1\cdot10^{-4}$
4	Boxes of RVNO and VYaP type	0.228	$0.595\cdot10^{-4}$	$0.42\cdot10^{-4}$
5	Transformer points within the pit and at dumps	0.111	$0.595\cdot10^{-4}$	$0.29\cdot10^{-4}$
6	Pit power supply points with disconnection devices	2.3	$0.595\cdot10^{-4}$	$2.36\cdot10^{-4}$
7	Excavator electrical equipment (upstream of disconnection device)	0.6	$0.595\cdot10^{-4}$	$1.1\cdot10^{-4}$
8	Daylight surface overhead power line	0.402	$0.595\cdot10^{-4}$	$1.3\cdot10^{-4}$
9	Overhead power line between substations	0.302	$0.595\cdot10^{-4}$	$0.86\cdot10^{-4}$
10	Collecting busbars with maximum protection on outgoing feeders in case of incorrect operation of protections for one emergency shutdown of protections	–	$0.35\cdot10^{-6}$	–
11	Connections	0.098	–	$0.35\cdot10^{-4}$

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$$T = np_3 t, \quad (9)$$

where n is the total number of failures on feeders outgoing from the busbars; t is the statistical mean duration of busbar downtime during the protection malfunction.

The influence of the protection operation on the scheme reliability is determined from the expression

$$P_n = \frac{T}{8760} = \frac{np_3 t}{8760}. \quad (10)$$

Methodology of reliability analysis of schemes

When assessing the reliability of electrical schemes, a special place is taken by substations and distribution points (DP) busbars, whose reliability indicators depend not only on the accident rate of the busbars themselves, but also on the number of failures on feeders outgoing from them and the protections function. Thus, the probability of interruption of power supply to load A (Fig. 4) is influenced not only by the failure of the circuit through which power is transmitted, but also by the failure of other feeders outgoing from busbar *2*.

Therefore, bus bars *2* (see Fig. 4) with feeders outgoing from them shall be replaced by another conditional component, for example, a component with an accident rate equal to the sum of the accident rate of the busbars and the probability of coincidence of failures on feeders with protection malfunction. Then, to determine the probability of interruption of power supply to load A, we obtain a design circuit of series-connected components (Fig. 5), from which:

$$P_A = \sum p_i, \quad (11)$$

where p_i is the probability of failure of individual components in the design circuit.

When determining the probability of failure of conditional component Ш for another receiver, for example, Б, the number of emergency disconnections of outgoing feeders may be slightly different than for load A and is due to a difference in the number of failures on the loads A and Б feeders. This difference is very small compared to the total number of failures on the outgoing feeders, so in practical calculations it can be neglected and the probability of failure of component Ш can be assumed to be the same for all receivers (feeders). Further presentation of the methodology for determining the reliability indicator is made on a specific example (Fig. 6).

We determine the reliability indicators of substations 1, 2, 3, 4 and the whole network if:

Variant I

1. The probability of failure of connections between substations is equal to a, b, c, d, and e.

2. The receiver capacities of substations 1, 2, 3, 4 have the following ratios: $N_1 : N_2 : N_3 : N_4 = 2 : 3 : 5 : 2$.

3. The capacity of the connections is equal to: $N_{A-1} = N_{A-3} = N_1 + N_2 + N_3 + N_4$, $N_{1-2} = N_2 + N_3 + N_4$, $N_{2-3} = N_1 + N_2$.

4. The reliability of substation operation is equal to 1, the protection at all substations is ideal.

For substation 4, the accident rate of the scheme section from district substation *A* to substation 3, which has two parallel branches with failure probabilities b, $a + c + d$, is equal to $b(a + c + d)$. Consequently, the considered scheme for substation 4 can be replaced by the scheme shown in Fig. 7, from which the probability of interruption of power supply to substation 4 is equal to: $P_4 = b(a + c + d) + e$.

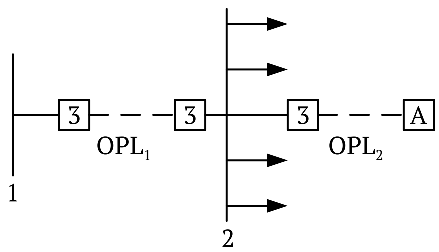

Fig. 4. Design circuit of the electrical grid: OPL – Overhead Power Line

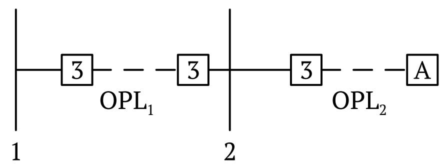

Fig. 5. Design circuit of series-connected components: OPL – Overhead Power Line

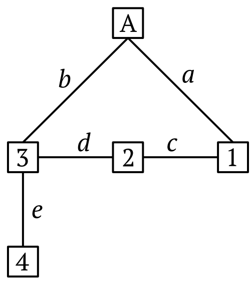

Fig. 6. Example of presentation of the methodology for determining the reliability indicator

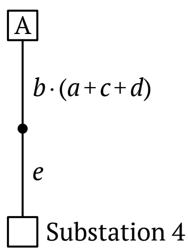

Fig. 7. Replacement of the scheme in Fig. 6

The probabilities of interruption of power supply to substations 1, 2, 3 are equal to: $a(c + b + d)$, $(a + c)\cdot(b + d)$, $b(a + c + d)$ respectively.

Variant II

Let us modify condition 3 and assume that $N_{A-1} = N_1 + N_2 + N_3$, $N_{A-3} = N_1 + N_2 + N_3 + N_4$, $N_{1-2} = N_2 + N_3$, $N_{2-3} = N_1 + N_2$.

The probability of interruption of power supply to substations 1, 2, 3 does not change, but the probability of scheme failure in relation to substation 4 changes significantly, because connection A–1–2–3 to substation 3 in case of failure of connection A–3 is not able to power substation 4. The probability of interruption of power supply to substation 4 is determined by the failure of connections A–3 and 3–4 and is equal to: $P'_4 = b + e$.

Thus, the same scheme with the same loads depending on the capacities of separate scheme sections has different reliability indicators.

Variant III

Let us change condition 2 and accept that $N_1 : N_2 : N_3 : N_4 = 5 : 1 : 2 : 4$.

The values of probabilities of power supply interruption to individual substations do not change, but the capacity of the receivers of each substation, kW·h, does change. Therefore, a change in the ratio between the substation capacities of the scheme under study changes the duration of downtime of the whole scheme receivers. Therefore, the sum of probabilities of power supply interruption to individual substations (receivers without taking into account their capacities) cannot be a reliability indicator of the whole scheme. The capacities of substations (receivers) can be taken into account, if the probability of power supply interruption to substations is brought to the same capacity, for example, to the total capacity of all substations, by multiplying them by the ratio of capacities of individual substations to their total capacity. The obtained new values of the probability of power supply interruption to individual substations, which have the same significance from the duration of downtime of receivers standpoint, allow modifying the scheme under consideration into a single-line scheme with one conditional receiver, whose capacity is equal to the sum of the capacities of all substations (receivers).

Modification according to the conditions of the considered scheme variants is shown in Fig. 8.

The results of probability calculations for power supply interruption to all scheme receivers, assuming that $a–b–c–d–e$, are equal to:

Variant I – $3\frac{1}{4}a^2 + \frac{1}{6}a$,

Variant II – $2\frac{3}{4}a^2 + \frac{1}{3}a$,

Variant III – $3\frac{1}{12}a^2 + \frac{1}{3}a$.

Thus, the reliability analysis of schemes should be performed as follows:

1. Replace the busbars of substations and distribution substations with conditional components $Ш_i$, whose failure probability is determined by the sum of the probability of failures of the busbars themselves and the probability of coincidence of failures on outgoing feeders with protections malfunction.

2. Determine the probability of power supply interruption to each receiver (substation), taking into account the capacities of individual scheme sections. In case of complex schemes, to simplify the calculation, convert them into design circuits for each receiver (substation).

3. Reduce the probabilities of power supply interruption to individual loads to their total capacity and, using the probabilities given, make a design circuit with one conditional load of the total capacity.

4. Determine the probability of power supply interruption to all receivers of the scheme.

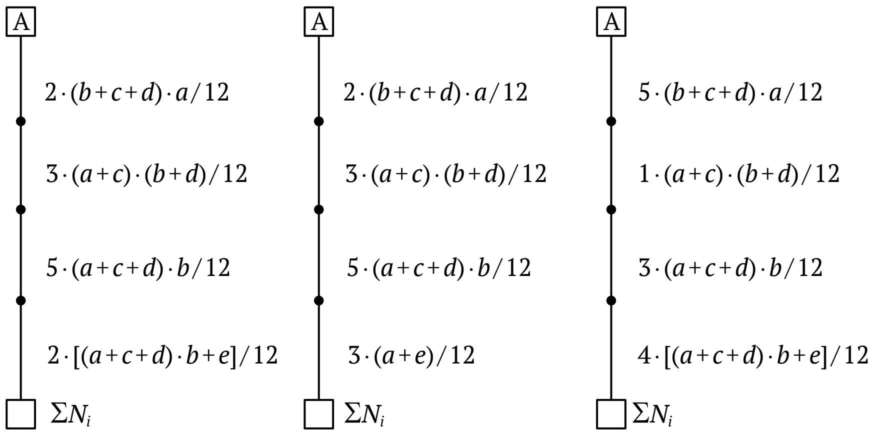

Fig. 8. Modification according to the conditions of the considered scheme variants

Methods of optimizing open-pit power supply systems

The central problem in the development of any CAD subsystem is to determine the optimal parameters of this subsystem. Only in this case the advantages of designing automation can be realized in full [17, 18].

The variety of the content of practical problems reflected in the existing mathematical models is so great that it is usually necessary to investigate many ways to achieve the optimum. None of the optimization methods is universal from the application to any particular problem standpoint, but also does not act in isolation from others.

An optimization problem can be mathematically formulated as follows: there is function F of several variables X_n. These variables are related to each other by k-equations or inequalities of the form:

$$\begin{aligned} &W_1(X_1, X_2, ..., X_n) \geq 0; \\ &... \\ &W_k(X_1, X_2, ..., X_n) \geq 0, \end{aligned} \tag{12}$$

where W_1, W_k are some functions of variables X_i ($i = 1, 2, ..., n$).

It is required to find the minimum (maximum) of function F. Three directions for solving the above problem can be distinguished based on the application of:

– first-order gradient methods;

– second-order methods or so-called quadratic optimization methods;

– random search methods.

A group of gradient methods is the most widespread for solving nonlinear programming problems, among which the method of steepest descent should be considered primarily.

The search for the minimum using the method of steepest descent consists in the sequential application of the following expression for the calculation of the main variables:

$$X_j^{(k+1)} = X_j^{(k)} + h\frac{\partial \Phi}{\partial X_j^{(k)}}, \tag{13}$$

where $X_j^{(k+1)}$ are the refined values of the required parameters at the $(k+1)$-th iteration; $X_j^{(k)}$ is the value of parameters at the k-th iteration; h is the coefficient of the length of increment; $\partial\Phi/\partial X_j^{(k)}$ are the values of particular derivatives from the target function for the main variables at the k-th iteration.

It is convenient to present the values of derivatives at the sequential iteration in the form of a matrix.

The increment length coefficient can be calculated by the formula:

$$h = \frac{\sum_{j=1}^{n}\left(\frac{\partial \Phi}{\partial X_j}\right)^2}{\sum_{j=1}^{n}\sum_{k=1}^{n}\left(\frac{\partial^2 \Phi}{\partial X_j \partial X_k}\frac{\partial \Phi}{\partial X_j}\frac{\partial \Phi}{\partial X_k}\right)}. \tag{14}$$

Let it be necessary to minimize function $U(Z)$ with a continuous gradient under constraints: $W(Z) = 0$, $Z_{\min} \leqslant Z \leqslant Z_{\max}$.

The vector of parameters Z is presented as a set of vectors X and Y (dependent and independent parameters). In this case, the problem can be presented as minimization of an implicit function:

$$U[X(Y), Y] = И(Y). \tag{15}$$

With constraints: $X_{\min} \leqslant X(Y) \leqslant X_{\max}$, $Y_{\min} \leqslant Y \leqslant Y_{\max}$, where $X(Y)$ is an implicit function determined by the steady-state condition equation:

$$W(X, Y) = 0. \tag{16}$$

The problem is proposed to be solved in two stages: entering the mode into the permissible region and determining the minimum of the target function in the permissible region.

Let there be a problem of entering the mode into the permissible region. With $Y^{(0)}$, $X = X^{(0)}$ is calculated from equation (16). Corrections ΔX to initial approximation vector $X^{(0)}$ are determined by the equation:

$$\frac{\partial W}{\partial X}\Delta X = -W, \tag{17}$$

where $\partial W/\partial X$ is the matrix of particular derivative functions.

Based on (15), the gradient is calculated:

$$\frac{\partial И}{\partial Y} = \left.\frac{\partial И}{\partial Y}\right|_0 = \frac{\partial И}{\partial X}\frac{\partial X}{\partial Y}, \tag{18}$$

where

$$\frac{\partial X}{\partial Y} = \left[\frac{\partial W}{\partial X}\right]^{-1}\frac{\partial W}{\partial Y}. \tag{19}$$

The permissible vector of descent (V) is obtained from the gradient by replacing with zeros the components of the corresponding variables that are on the boundary and tend to go beyond the permissible limits and change the sign of the remaining components.

The following approximation of vector Y:

$$Y^{(1)} = Y^{(0)} + Vt = Y(t), \tag{20}$$

where $t = \min(t_n, t_{ul})$.

Value t_n is determined by the Newton method from expression:

$$V\frac{\partial И}{\partial Y}(t) = 0. \tag{21}$$

Ultimate increment $t_{ul} = \min(t_{iul})$ is the solution of the equation:

$$Z_i[Y(t)] - Z_{iul} = 0, \tag{22}$$

where

$$Z_{iul} = \begin{cases} Z_{iul_{\max}} & \text{at } \dfrac{\partial Z}{\partial t} < 0, \\ Z_{iul_{\min}} & \text{at } \dfrac{\partial Z}{\partial t} > 0. \end{cases} \tag{23}$$

The end of the computational optimization process is controlled by value V, taking into account the changes in vector Y and $И(Y)$ over a number of successive approximations.

The disadvantages of this method include worsening of convergence when approaching the minimum of the target function, as well as the complexity of the algorithm and the labor intensity of its implementation.

To take into account inequality-type constraints when applying gradient methods, it is proposed to use the penalty function method.

In the literature, a network of gradient-based optimization methods is given and their comparative characteristics are provided.

The most powerful optimization method based on the first-order gradient method is designed to solve problems minimizing the function:

$$И = \sum_{i=1}^{k} И_i(X). \tag{24}$$

Compared to the reduced gradient method, the steady-state equation is written in the form of explicit functions, and the functional constraints are controlled by penalty functions, whereas in the reduced gradient method they are controlled by changing the basis, i.e., by exchanging variables of vectors X and Y.

Optimization methods of the second direction have been widely used in numerous studies.

A method of solving the problem of integrated optimization is known. The basic idea is to modify an initially nonlinear problem with constraints into a sequence of problems without constraints, whose solution approaches the solution of the original problem. The modified problem is solved by the Fletcher–Powell method [19].

Different methods of modifying the original problem are analyzed in scientific papers. The analysis of the Fiacco and McCormick, Zangwill, and Powell [20] methods showed the expediency of the latter two methods as not requiring an initial point satisfying inequality-type constraints.

Using the Zangwill's transformation corresponding to the application of penalty functions, the following unconstrained function is formulated:

$$F(X) = И(X) + \sum_{i=1}^{r} r_i \cdot W_i(X)^2 + \sum_{j=1}^{p} r_j \cdot g_j(X)^2. \tag{25}$$

In equation (25), term $g_j(X)$ representing an inequality-type constraint exists only when this constraint is violated.

According to the Fletcher–Powell method, for quadratic function $f(X)$ the following ratio is true:

$$f(\bar{X} - X) = l_j g(X), \tag{26}$$

where $\bar{X}$ is the point of maximum; l_j is the reverse matrix of the second partial derivatives of function $f(X)$, called the Hesse matrix; $g(X)$ is the vector of the first partial derivatives of function $f(X)$.

The difference in the left-hand side of ratio (26) represents the distance between any point X and the point of minimum. For a non-quadratic function, $\bar{X}$ is not an exact minimum, but this point can be considered as an initial approximation for the sequential iteration by expression (26).

Matrix l_j is obtained iteratively by an algorithm that requires only the first derivatives of the target function. After determining ΔX and a new point of matrix l_j, which was initially singular, matrix l_j is recalculated by adding the coefficient matrices to it:

$$l_j^{(i+1)} = l_j^{(i)} + A^{(i)} + B^{(i)}, \tag{27}$$

where

$$B_{jk}^{(i)} = \frac{(l_j^{(i)} Y^{(i)})_j (Y^{(i)T} l_j^{(i)})_k}{Y^{(i)T} l_j^{(i)} Y^{(i)}},$$

$$A_{jk}^{(i)} = \frac{\Delta X_j^{(i)} \Delta X_k^{(i)}}{\Delta X^{(i)T} Y^{(i)}},$$

$$Y^{(i)} = \frac{\partial f^{(i+1)}}{\partial X} - \frac{\partial f^{(i)}}{\partial X}.$$

The peculiarity of the Fletcher–Powell method is that there is no need to compute the inverse matrix of the second partial derivatives.

The disadvantages of the method include: (1) the Hesse matrix shall be permanently stored in the computer core memory and changed at each step of the algorithm; (2) when solving problems with a large number of variables, changes in matrix l_j may be insufficient to obtain such values of ΔX that would reduce $f(X)$.

To eliminate these disadvantages, the idea of direct estimation of the Hesse matrix is proposed:

$$H\Delta X = g(X), \tag{28}$$

where H is the Hesse matrix.

Equation (28) is solved relative to ΔX using Gauss elimination, which consists in reducing the system to a triangular form. The main disadvantage of the method is its dependence on the choice of the starting point.

Statistical methods for optimizing power supply systems are outlined and have been developed by D.A. Arzamastsev [21]. The formulation of the problem of the electric grid mode complex optimization is considered. The combination of random search with the penalty function method makes it possible to determine conditional extrema for the problem of optimization of the electrical grid and system operation mode.

In the permissible region of the k-factor space under study, starting point $X^{(0)}$ is chosen with coordinates $X_1^{(0)}, X_2^{(0)}, \ldots, X_k^{(0)}$, and the value of target function $T^{(0)}$ is calculated in it. To move to new point $X^{(1)}$ with coordinates $X_1^{(1)}, X_2^{(1)}, \ldots, X_k^{(1)}$, a random vector is selected, which is evenly distributed over a hyposphere of radius h with the center in the coordinate origin:

$$\Delta\bar{X}^{(0)} = (\Delta X_1^{(0)}, \Delta X_2^{(0)}, \ldots, \Delta X_k^{(0)}). \quad (29)$$

Coordinates of point $X^{(1)}$ are determined by summing up two vectors:

$$\bar{X}^{(1)} = \bar{X}^{(0)} + \Delta\bar{X}^{(0)}. \quad (30)$$

The value of the target function in point $X^{(1)}$ is equal to $T^{(1)}$.

The completed step is considered successful and point $X^{(1)}$ is accepted if the following condition is fulfilled:

$$T^{(1)} < T^{(0)}. \quad (31)$$

Otherwise, point $X^{(1)}$ is not accepted. Once again a random vector is selected and a new attempt to make a successful step is made. The process of transfer from point $X^{(1)}$ to point $X^{(2)}$ is performed in the same way.

The advantage of the random search method is the simplicity of the structure of program implementation on the computer, high reliability and efficiency in solving many nonlinear programming problems. It is the only method capable of solving multiextremal problems. It is especially effective in the absence of analytical expressions for the gradient. At the same time, when approaching the minimum of the target function using the random search algorithm, the number of unsuccessful steps increases, so it is advisable to do refinement near the extremum using some deterministic optimization method, such as gradient.

A variety of the random search method is the random descent method.

When determining the minimum of the target function according to a random descent algorithm, the direction of motion is generally given by a random vector uniformly distributed over a hyposphere. However, unlike the random search algorithm, the direction is not chosen at every step. In the randomly selected successful direction, a number of working steps are performed until the function starts to increase. At the resulting point, a successful direction is selected again, and descent is performed in that direction until it is exhausted, and so on. Thus, a descent to the region of the required minimum is performed.

Conclusion

The existing power supply schemes of open-pit mines have been analyzed from the standpoint of the accident rate of separate network components and electrical equipment of open pits and the influence of various disturbing factors on it. The analysis for all main components of open-pit power supply schemes showed that the time of emergency downtime and the time of emergency shutdown is subject to the log-normal distribution, and the standard of the modifying function argument practically keeps a constant value. The conducted analyses show that the annual durations of emergency downtime of open-pit electrical equipment are also distributed according to the log-normal distribution and the values of the modified argument standard have deviations not exceeding 20% of the determined standard mean value of 0.347. The method of reliability analysis of schemes for several variants has been developed. It consists in determining the probability of power supply interruption to each receiver (substation), taking into account the capacities of individual scheme sections and individual loads in relation to their total capacity. Methods of optimizing the open-pit power supply systems are presented, which consist in the use of first-order gradient methods, second-order methods or the so-called quadratic optimization methods, and random search methods. A group of gradient methods is the most widespread for solving nonlinear programming problems, among which the method of steepest descent should be considered primarily. The method of random descent, which consists in determining the minimum of the target function according to an appropriate algorithm, is also considered, in which the direction of motion is generally given by a random vector uniformly distributed over a hyposphere.

References

1. Pirogov G.G. The principles of opening ore deposits in the development on the basis of underground mining complexesю *Scholarly Notes of Transbaikal State University. Series Physics, Mathematics, Engineering, Technology*. 2017;12(4):73–79. (In Russ.) https://doi.org/10.21209/2308-8761-2017-12-4-73-79
2. Kaplunov D.R., Lomonosov G.G. Main problems of subsoil development during underground mining of ore deposits. *Gornyi Zhurnal*. 1999;(1):42–45. (In Russ.)
3. Tugai Yu.I., Gai A.V., Stachniuk S.V. The model's construction of power system reliability based on using Monte Carlo simulation. *Agrotekhnika i Energoobespecheniye*. 2015;1(5):96–107. (In Russ.)

4. Ershov S.V., Demyanov D.V. The definition of indicators of system of power supply enterprise. *Izvestiya Tula State University. Technical Science*. 2017;(12–1):118–125. (In Russ.)
5. Corrigan C.C., Ikonnikova S.A. A review of the use of AI in the mining industry: Insights and ethical considerations for multi-objective optimization. *The Extractive Industries and Society*. 2024;17:101440. https://doi.org/10.1016/j.exis.2024.101440
6. Yaakoubi Y., Dimitrakopoulos R. Learning to schedule heuristics for the simultaneous stochastic optimization of mining complexes. *Computers & Operations Research*. 2023;159:106349. https://doi.org/10.1016/j.cor.2023.106349
7. Suslov N.M., Chernukhin S.A., Suslov D.N. Increasing energy efficiency of walker dragline. *News of the Ural State Mining University*. 2020;(3):131–139. (In Russ.) https://doi.org/10.21440/2307-2091-2020-3-131-139
8. Klyuev R.V., Bosikov I.I., Gavrina O.A., Lyashenko V.I. Assessment of operational reliability of power supply to developing ore mining areas at a high-altitude mine. *Mining Science and Technology* (*Russia*). 2021;6(3):211–220. (In Russ.) https://doi.org/10.17073/2500-0632-2021-3-211-220
9. Petrov V.L., Pichuev A.V. Hazard assessment of asymmetric modes for leakage current flowing through insulation in underground mine electrical grids. *Energy Safety and Energy Economy*. 2022;(5):15–22. (In Russ.)
10. Klyuev R.V., Golik V.I., Bosikov I.I., Gavrina O.A. Ensuring electrical safety of a mountain quarry by choosing selective relay protection in the electrical networks with the voltage above 1 kV. *Occupational Safety in Industry*. 2021;(9):31–37. (In Russ.) https://doi.org/10.24000/0409-2961-2021-9-31-37
11. Pelipenko M.V., Balovtsev S.V., Aynbinder I.I. Integrated accident risk assessment in mines. *Mining Informational and Analytical Bulletin*. 2019;(11):180–192. (In Russ.) https://doi.org/25018/0236-1493-2019-11-0-180-192
12. Kulikova E.Yu., Balovtsev S.V. Risk control system for the construction of urban underground structures. In: *IOP Conference Series: Materials Science and Engineering. International Conference on Construction, Architecture and Technosphere Safety (ICCATS 2020)*. 6–12 September 2020, Sochi, Russia. 2020;62(4):042020. https://doi.org/10.1088/1757-899X/962/4/042020
13. Cabral E.A., Tofoli F.L., Sampaio R.F., Leão R.P.S. Reliability assessment applied in the design of an industrial substation in the context of Industry 4.0. *Electric Power Systems Researc*h. 2024;231:110365. https://doi.org/10.1016/j.epsr.2024.110365
14. Singh K., Kalra Sh. Reliability forecasting and accelerated lifetime testing in advanced CMOS technologies. *Microelectronics Reliability*. 2023;151:115261. https://doi.org/10.1016/j.microrel.2023.115261
15. Jia Q., Fu G., Xie X. et al. Enhancing accident cause analysis through text classification and accident causation theory: A case study of coal mine gas explosion accidents. *Process Safety and Environmental Protection*. 2024;185:989–1002. https://doi.org/10.1016/j.psep.2024.03.066
16. Li W., Wang L., Ye Zh. et al. A dynamic combination algorithm based scenario construction theory for mine water-inrush accident multi-objective optimization. *Expert Systems with Applications*. 2024;238(A):121871. https://doi.org/10.1016/j.eswa.2023.121871
17. Pevzner L.D., Kiselev N.A. Automatic control system for walking dragline excavator digging. *Mining Science and Technology* (*Russia*). 2022;7(1):57–65. https://doi.org/10.17073/2500-0632-2022-1-57-65
18. Sokolov A.A., Orlova L.G., Bashmur K.A. Ensuring uninterrupted power supply to mining enterprises by developing virtual models of different operation modes of transformer substations. *Mining Informational and Analytical Bulletin*. 2023;(11–1):278–291. (In Russ.) https://doi.org/10.25018/0236_1493_2023_111_0_278
19. Yokoyama K., Yoshii A., Adachi T., Kasai R. Application of Fletcher-Powell's optimization method to process/device simulation of MOSFET characteristics. *Solid-State Electronics*. 1982;25(3):201–203. https://doi.org/10.1016/0038-1101(82)90108-3
20. Sieniutycz S., Jeżowski J. 1 – Brief review of static optimization methods. In: *Energy Optimization in Process Systems and Fuel Cells*. 3rd Edition. Elsevier; 2018. Pp. 1–41. https://doi.org/10.1016/B978-0-08-102557-4.00001-3
21. Misrikhanov M.Sh., Rusina A.G. Innovative approach to solving regime problems in managing electric power systems. *Vestnik of Ivanovo State Power Engineering University*. 2012;(3):22–27. (In Russ.)

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