 ISSN 2226-3780

11. Shutler N. D. Numerical, Three-Phase Simulation of the Linear Steamflood Process // Society of Petroleum Engineers Journal. 1969. Vol. 9, Issue 2. P. 232–246. doi: http://doi.org/10.2118/2233-pa
12. Lapin V. Ob issledovanii nekotorykh nelineynykh zadach teorii fil'tratsii // Zhurnal vychislitel'noy matematiki i matematicheskoy fiziki. 1979. Vol. 19, Issue 3. P. 689–700.
13. Abou-Kassem J. H., Farouq-Ali S. M. Petroleum Reservoir Simulations. Gulf Publishing Company, 2006. 445 p.
14. Samarskiy A. A. Teoriya raznostnykh skhem. Moscow: Nauka, 1984. 656 p.
15. Killough J. E. Reservoir Simulation With History-Dependent Saturation Functions // Society of Petroleum Engineers Journal. 1976. Vol. 16, Issue 1. P. 37–48. doi: http://doi.org/10.2118/5106-pa

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DIAGNOSTICS OF THE PRE-FAULT SITUATION OF THE BOLTED CURRENT-CARRYING JOINT IN THE CONDITIONS OF CHANGING REGIME PARAMETERS

Об'єктом дослідження є методи неруйнівного контролю болтового струмоведучого з'єднання в умовах динамічно змінюваних режимів струмового навантаження і температури навколишнього повітря. Одним з найбільш проблемних місць в сучасних умовах економічного розвитку підприємств є зниження аварійності виробництва через ослаблення болтового струмоведучого з'єднання. Проведені дослідження причин зупинки електроустаткування на ряді підприємств чорної металургії, гірничо-переробних комплексів, в медичних установах показали, що у 1,5–2 % випадків причиною аварійної зупинки електроустаткування є ослаблення болтового струмоведучого з'єднання. Основною проблемою болтового струмоведучого з'єднання є механічне ослаблення щільності контактів. На появу градієнта температур в місці болтового з'єднання впливають кліматичні параметри і динамічно змінювані режими експлуатаційних струмових навантажень і напруги мережі.

В основу дослідження режимних параметрів мережі і струмів навантаження лягло використання методики контролю показників якості електроенергії за допомогою самописних аналізаторів спектра. В даному дослідженні використано аналізатор спектру «Флюк 435» (Україна), характеристики якого відповідають сертифікату системи вимірювань ISO 9001. А в основі обробки експериментально отриманих даних використані методи статистичної обробки.

В ході дослідження визначено нерівність між виміряною температурою болтового струмоведучого з'єднання і розрахунковою температурою справного з'єднання. Нерівність виконується на ділянках, стаціонарності яких визначені для детермінованих і випадкових режимів зміни контрольованих параметрів. Складені функції булевих змінних, мінімізовані диз'юнктивні функції, що визначають нормальний і передаварійний режими болтового з'єднання. Отримані теоретичні результати дозволили розробити алгоритми та пристрій для діагностики і захисту обладнання.

Завдяки цьому забезпечується можливість знизити аварійність роботи обладнання. У порівнянні з аналогічними відомими засобами захисту обладнання облік режимів струмів навантаження, напруги мережі і температури навколишнього повітря забезпечує високу чутливість і достовірність виявлення початкового моменту ослаблення болтового струмоведучого з'єднання.

Ключові слова: *ослаблення болтового струмоведучого з'єднання, діагностика стану, випадковий і детермінований режими струму навантаження.*

1. Introduction

In the power transmission system, the joints of the electric power supply chain of enterprises in 40 % of cases are carried out using bolted joints. Studies of the causes of stopping electrical equipment (EE) at a number of ferrous metallurgy enterprises, mining processing complexes, and medical institutions showed that in 1.5–2 % of cases the cause of an fault shutdown of an EE is a weakening of the bolted current-carrying joint (BCJ) [1, 2].

The main BCJ problem is a mechanical weakening of the density of the adjacent surfaces of busbars, cable lugs, switching equipment joints, etc. Mechanical weakening leads to an increase in contact resistance at the place of the booth joint, even if the permissible load current flows through it, which causes BCJ overheating. BCJ overheating is one of the causes of short circuits in switchboards and the formation of fire sources [3]. Identification of the initial moment of BCJ weakening allows for timely preventive maintenance and avoiding fault situations.

Therefore, it is urgent to develop methods for diagnosing the BCJ state operating under conditions of dynamically changing current load conditions and the temperature of the air surrounding BCJ.

2. The object of research and its technological audit

The object of research is the methods of non-destructive monitoring of the BCJ state under conditions of dynamically changing current load conditions and ambient temperature.

The appearance of a temperature gradient at the bolted joint affected by the change in climatic parameters, ranging from −25 °C to 50 °C and dynamic changes in operating current load conditions. Dynamic change of current in the range $(0.1–1.1)\cdot I_n$, where I_n is the rated load current, is associated with the technological mode, and short-term change in currents to $(5–7)\cdot I_n$ is in the starting mode. Permanent electrodynamic forces in BCJ with a frequency of 100 Hz, arising from the flow of current in adjacent wires, and dynamic deviations of the mains voltage within ±10 % U_n cause additional changes in the current flowing in the BCJ. These factors acting on the BCJ, are the cause of their weakening [4]. And these factors are not well understood at this time.

3. The aim and objectives of research

The aim of research is studying the effect of randomly varying voltage levels on the magnitudes of the load currents and temperature changes in the BCJ.

To achieve this aim it is necessary to perform the following objectives:

1. To improve the thermal method of non-destructive monitoring of the BCJ state for the timely detection of a pre-fault situation in case of non-stationary and random modes of change in the current flowing in the BCJ.
2. To develop criteria for detecting the pre-fault situation of a BCJ in the conditions of non-stationary and random modes of current change.

4. Research of existing solutions of the problem

To diagnose the BCJ state, the thermal method of non-destructive testing [5] is widely used, both by contact and without contact, which allows detecting the BCJ fault state without disturbing the process.

The known methods for diagnosing the BCJ condition include such as:

– installation of fusible marks with low-melting solder (Rose's alloy) and contact temperature measurement [6];
– thermal control [7];
– use of pasted color-sensitive indicators;
– installation of bimetallic plates under the BCJ screw, etc.

And to the known devices for diagnosing the BCJ state are those in which:

– control the BCJ temperature [8, 9];
– produce control of the BCJ load current and temperature [10].

These methods react to the fault state of a weakened bolted joint, that is, to a BCJ temperature exceeding the critical value. Monitoring only the BCJ temperature does not allow to diagnose the initial moment of BCJ weakening, that is, to identify a pre-fault situation.

Among the main directions of solving the problem of diagnosing the BCJ state can be distinguished [3, 4], in which the thermal imaging method of measuring the BCJ temperature is used. These methods for monitoring the BCJ integrity are episodic in nature and are used as an additional diagnostic for the BCJ state during routine inspections of the EE. The works [5, 6] are devoted to contact measurement of the BCJ temperature. In these methods, the achievement of the critical BCJ temperature is a criterion for determining the BCJ fault state and disconnecting the EE from the network. These solutions do not reveal the initial moment of BCJ weakening. In [7], the analysis of the use of infrared radiation to monitor the EE state is performed. However, in this work the use of the phenomenon is not fully disclosed for the BCJ diagnosis.

The authors of [8, 9] show that using the contact method of monitoring the BCJ state is the most promising, but the question remains of identifying the initial moment of BCJ weakening with changes in load current, supply voltage modes and ambient temperature of the air around BCJ. An alternative solution to the problem, described in [10], provides for the simultaneous control of the load current and the ambient temperature at steady state current load.

The author of [11, 12] emphasizes the importance of simultaneously monitoring the BCJ temperature, ambient air temperature and load current. In these studies, the thermal method of non-destructive testing has been improved; however, the method works only with stationary modes of current and air temperature variation.

Thus, the results of the analysis allow to conclude that in order to increase the reliability of diagnostics of the pre-fault situation, namely, to identify the initial moment of BCJ weakening, it is necessary to take into account dynamic changes in the load current and temperature of the air around BCJ.

5. Methods of research

The process of mechanical BCJ weakening in the absence of external climatic, vibration factors and with the stationary nature of the current load, not exceeding $0.5I_n$, takes from several days to several months. An increase in the load current and the ambient temperature leads to overheating of the weakened BCJ above the critical temperature in 0.5–1 hours. Therefore, the implementation of episodic control of only the BCJ temperature is not enough to identify the moment of determining the BCJ weakening. To identify the pre-fault situation of BCJ weakening, according to [11, 12], the load current value and the dynamically changing parameters of the air around BCJ are also monitored. The control of additional quantities allows to reveal the initial moment of BCJ

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weakening. However, in these technical solutions [11, 12] the identification of the pre-fault situation of BCJ weakening is considered for stationary current load modes, supply mains voltages and air temperature. The condition for determining the initial moment of BCJ weakening in the devices [11, 12] is the inequality:

$$T_m > T_c, \tag{1}$$

where T_m – the measured BCJ temperature; T_c – calculated and corrected BCJ temperature:

$$T_c = \frac{I_c^2}{\alpha F} R_c + 24\ °\text{C} + \Delta T_a, \tag{2}$$

where α – the heat transfer coefficient; F – the surface area of the bolted joint; $\Delta T_a = (T_a - 24\ °\text{C})$ – increment of ambient temperature relative to 24 °C; $R_t = R_{bj} + R_{cr}$ – the total resistance of the bolted joint and contact resistance; I_c – the current flowing in the BCJ.

Expressions (1) and (2) show the functional dependence of the BCJ temperature on the load current, the ambient temperature and the magnitude of the transition resistance of the BCJ. In case of non-stationary and random change of current, as well as in transient modes of changing current and ambient air temperatures, the BCJ temperature changes with delay. The delay time depends on the continuous BCJ heating. At the time of reducing the current or ambient temperature, the value of the measured BCJ temperature remains above the temperature of the fault-free BCJ. This leads to a false determination of the initial moment of BCJ weakening and the false triggering of the EE protection device.

The nature of the change in current load is caused not only by the technological mode of operation of the equipment, but also by the influence of random factors. The voltage variation on the bus of the supplying substation can be random and depends on the characteristics of adjacent electrical consumers.

The study of operating parameters of the network and load currents was based on the use of a technique for monitoring the quality of electricity indicators using self-recording spectrum analyzers. In this study, let's the Fluk 435 spectrum analyzer (Ukraine), the characteristics of which correspond to the ISO 9001 measurement system certificate.

The processing of the experimentally obtained data is based on statistical processing methods [13].

Fig. 1 shows the oscillogram of the change in the load current of the X-ray computer tomograph model TSX-031 Alexsion 16 (Japan), passport No. PT-148-2012, 42 kW generator, anode voltage 135 kV. Fig. 1 shows the operation mode of the tomograph, which operates in a re-short-term mode and the stationary nature of the supply voltage of the network.

Fig. 2 shows an oscillogram of the change in the load current of an x-ray computed tomograph, operating with a non-stationary character of the supply voltage.

To identify the correlation dependence of the current flowing in the BCJ, when changing the voltage levels in the network, studies were performed by a statistical method. For the section where the change in the current value is not related to the technological process (Fig. 2), the calculations of the static current and voltage expectation are carried out according to the expression [13]:

$$M_I = \frac{1}{n}\sum_i^n I_i,\ M_U = \frac{1}{n}\sum_i^n U_i. \tag{3}$$

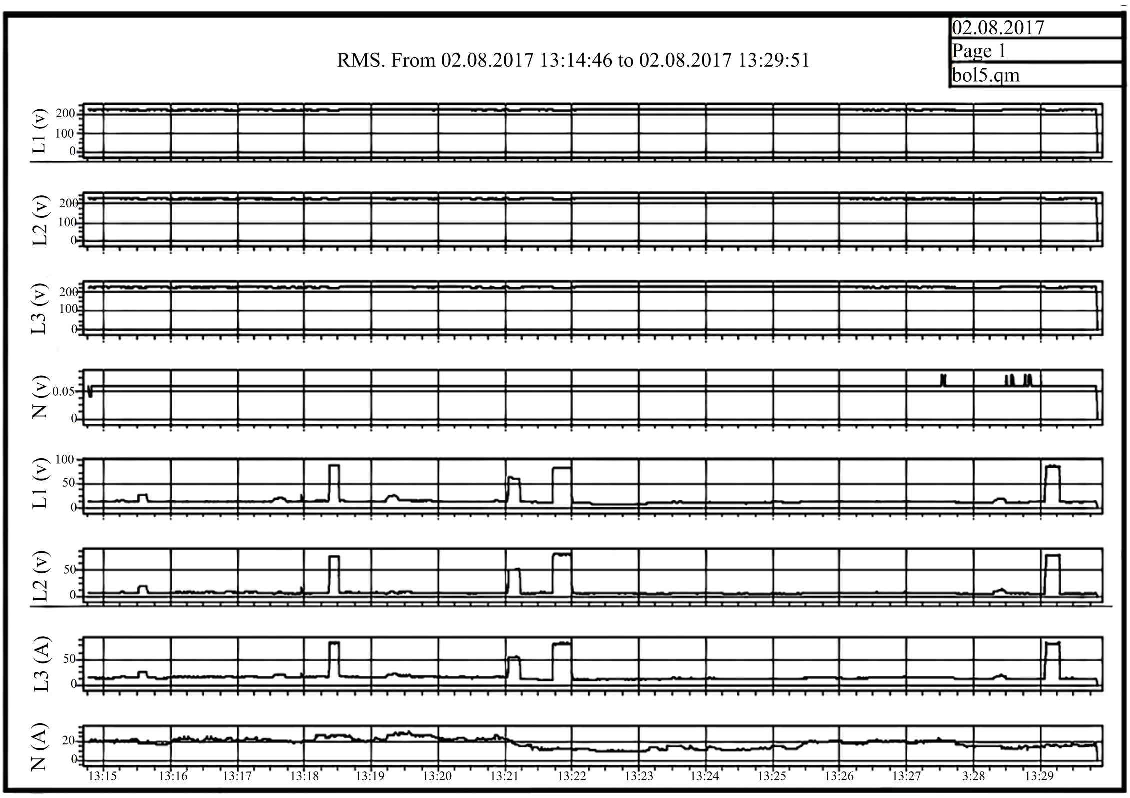

Fig. 1. Oscillogram of current consumption of an x-ray computed tomograph operating in a re-short-term mode and the stationary nature of the supply voltage

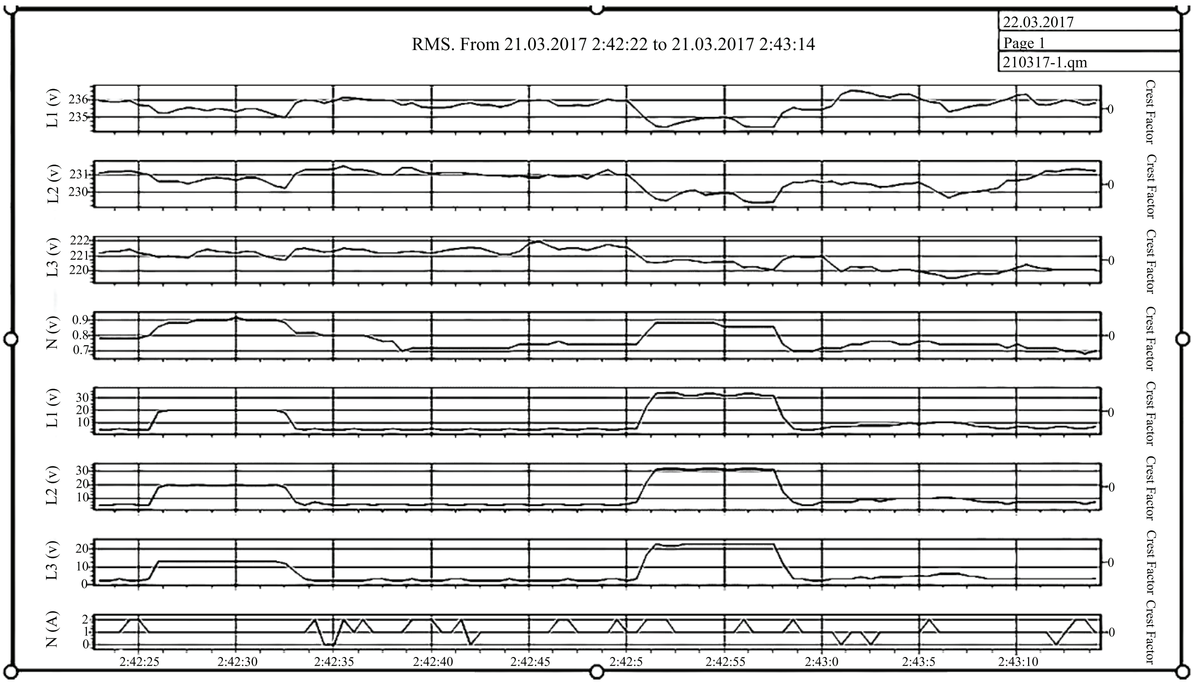

Fig. 2. Oscillogram of the change in the current of an x-ray computed tomograph, operating with the non-stationary nature of the supply voltage

As well as the static dispersion of current and voltage by the expression:

$$D_I = \frac{1}{n}\sum_{i}^{n}\left(I_i - M_I\right)^2,$$

$$D_U = \frac{1}{n}\sum_{i}^{n}\left(U_i - M_U\right)^2. \qquad (4)$$

Statistical standard deviation of the expression:

$$\sigma_I = \sqrt{D_I},\ \sigma_U = \sqrt{D_U}. \qquad (5)$$

And to identify the dependence degree of the change in current value on the change in voltage value, the static correlation moment is determined by the expression:

$$k_{I,U} = \frac{1}{n}\sum_{i=1}^{n}\left(I_i - M_I\right)\left(U_i - M_U\right). \qquad (6)$$

Table 1 shows the protocol for measuring the current values and voltages of the power consumer received during measurements (oscillogram Fig. 2).

The results of data processing are given in Table 1:

$M_I = 7.01$ A, $M_U = 235.86$ B, $D_I = 0.1$,

$\sigma_I = 0.32$, $D_U = 21.5$, $\sigma_U = 4.64$, $k_{I,U} = 2.07$.

At the correlation moment $k_{I,U} = 2.07$, the current and voltages associated with the correlation dependence, i. e., random changes in the values of the supply voltage, affect the nature of the change in the value of the current consumed.

Fig. 3 is a graph of the BCJ temperature change when stationary and deterministic changes in the BCJ current.

Fig. 4 is a graph of the temperature change of the BCJ during unsteady, deterministic and random changes in the current flowing in the bolted joint.

Table 1

Current and voltage measurement protocol

No.	I/A	U/B	No.	I/A	U/B	No.	I/A	U/B
1	7.1	238.6	11	6.8	232.1	21	7.3	242.1
2	7.2	239.0	12	7.4	241.0	22	7.4	2431
3	6.9	237.1	13	7.3	239.0	23	7.2	239.2
4	6.7	230.1	14	6.5	230.1	24	6.8	231.0
5	7.2	241.2	15	6.4	227.0	25	6.7	230.2
6	7.1	241.2	16	6.8	230.1	26	6.5	229.1
7	7.3	242.2	17	7.2	240.1	27	7.4	239.0
8	6.9	236.0	18	7.3	240.0	28	6.8	231.1
9	7.1	239.2	19	7.3	235.1	29	6.5	235.5
10	7.0	227.0	20	7.1	236.1	30	6.9	236.1

In Fig. 3, 4 there are:

1 – curve of the change in the calculated BCJ temperature at a constant ambient temperature;

2 – curve of BCJ temperature variation, when current flows in it;

3 – zones of false determination of the initial moment of BCJ weakening.

Reliable determination of the BCJ pre-fault condition for stationary, but deterministic mode of change of the load current and the ambient air temperature is possible in the stationary areas. Sites of stationarity are the simultaneous fulfillment of the conditions:

$$\frac{dI_n}{dt} = 0,\ \frac{dT_a}{dt} = 0,\ \frac{dT_c}{dt} = 0.$$

And only at these sites check the fulfillment of inequality (1).

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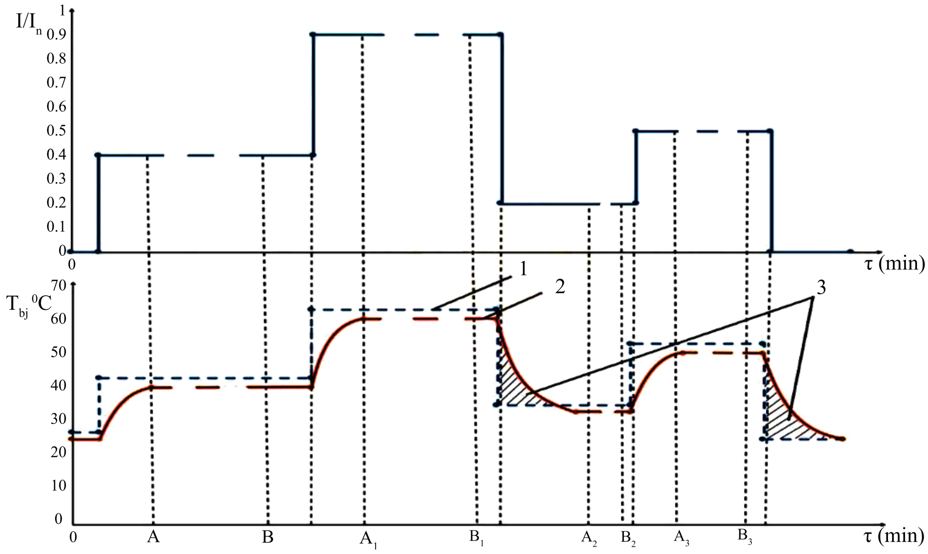

Fig. 3. The graph of the temperature change of the bolted current-carrying joint with a stationary and deterministic change in current

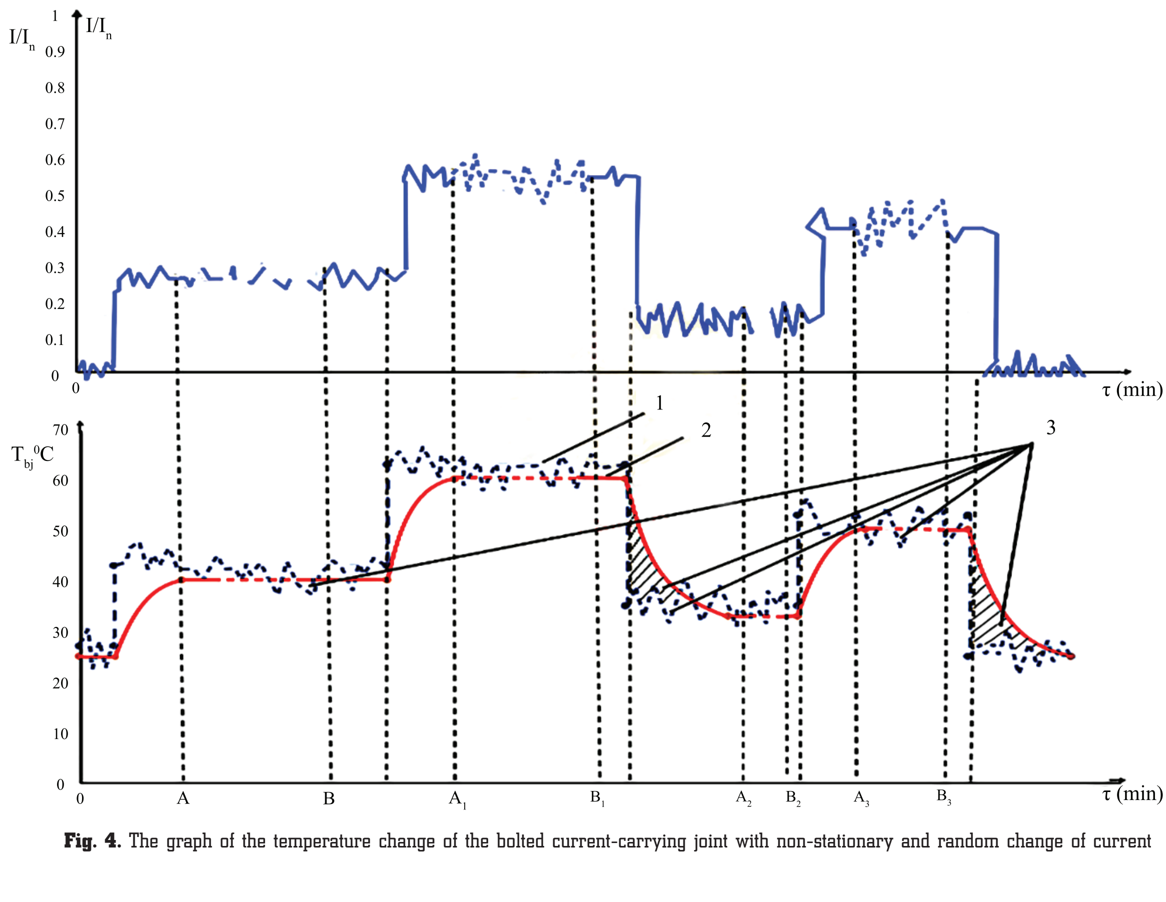

Fig. 4. The graph of the temperature change of the bolted current-carrying joint with non-stationary and random change of current

In order to reliably determine the BCJ pre-fault condition during a random and deterministic process of changing the load current and the ambient temperature, we convert the analog signals of the effective current, temperature of the bolted joint and ambient air to discrete values, with a sample equal to $n=50$ and the measurement interval:

$$\Delta t = \frac{T}{m50},$$

where T – the time interval for the study of the controlled parameter; m – the number of intervals of the studied parameter. For the numerical evaluation of the monitored parameters, let's determine the statistical expectation and statistical standard deviations, expressions (3) and (5).

The first condition for a stationary random function is that the expectation on the research interval must satisfy the condition:

$$M_x(t) = M_x = \text{const}. \quad (7)$$

The second condition, which, obviously, must be satisfied by a stationary random function, is the condition for the constancy of the variance on this interval:

$$D_x(t) = D_x = \text{const.} \quad (8)$$

Thus, temporary areas of stationarity to identify the initial moment of BCJ weakening with any changes in load current and ambient temperature are the following conditions:

$$M(I_l) = \text{const}, \ M(T_c) = \text{const}, \ M(T_a) = \text{const};$$

$$\sigma(I_l) = \text{const}, \ \sigma(T_c) = \text{const}, \ \sigma(T_a) = \text{const}.$$

The magnitude of the calculated and adjustable temperature of a fault-free bolted joint in the areas of stationarity is determined by the expression:

$$T_c = \left(\frac{\left(M(I_l)+\sigma(I_l)\right)^2}{\alpha F}\left(R_{bj}+R_{cr}\right) + 24\ ^\circ\text{C} \right) + \\ + \Delta\left(M_{Ta}+\sigma_{Ta}\right). \quad (9)$$

The value of the measured BCJ temperature is determined by the expression:

$$T_m = M_{Tm} - \sigma_{Tm}. \quad (10)$$

The obtained results of calculations of statistical indicators of the estimated temperature of a serviceable BCJ and statistical indicators of the measured temperature are checked by inequality (1).

6. Research results

The obtained theoretical dependences (1), (9) and (10) implemented in the device for diagnosing the state of current circuits and the initial moment of BCJ weakening [12], the block diagram of which is shown in Fig. 5.

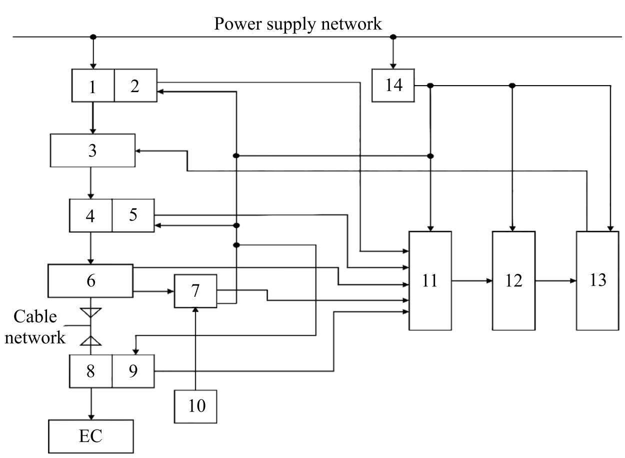

Fig. 5. Block diagram of the device for diagnosing the state of current circuits and bolted current-carrying joints

In Fig. 5:
1 – bolted assembly with bolt temperature sensors;
2 – unit for measuring the temperature of a bolted joint;
3 – switching device;
4 – bolted assembly with bolt temperature sensors;
5 – unit for measuring the temperature of a bolted joint;
6 – unit for measuring the strength of phase currents;
7 – unit for converting a current signal to an equivalent temperature signal and correction of this signal depending on a change in the ambient temperature;
8 – bolted joint with bolt temperature sensors;
9 – unit for measuring the temperature of a bolted joint;
10 – unit for measuring ambient temperature;
11 – block digital-analog signal conversion;
12 – microcontroller;
13 – control and alarm unit;
14 – power supply.

For the operation of the microprocessor of the device (Fig. 5), a computer program has been developed for BCJ diagnosing and protecting the EE when a pre-fault condition occurs. In compiling test tables of the BCJ state, a set of Boolean variables is used.

In order to reveal the initial moment of BCJ weakening for the stationary and continuous process of changing the current and the ambient air temperature, let's introduce the arguments of the Boolean variable characteristic of EE operating modes:

– X_1=«0» – logical zero – in the absence of current;
– X_1=«1» – logical unit – when current flows in the BCJ;
– $-X_2$=«1» – when inequality $(T_{cI}+(24\ ^\circ\text{C}-T_a))>(T_{bj})$ is met;
– X_2=«1» – when inequality $(T_{cI}+(24\ ^\circ\text{C}-T_a))<(T_{bj})$ is fulfilled;
– X_3=«0» – when inequality $(T_{bj})<(T_{cor})$ is met;
– X_3=«1» – when inequality $(T_{bj})>(T_{cor})$ is met.

The perfect disjunctive new form (PDNF), according to [13], describing the intact and faulty BCJ state, is the expression:

$$F = \left(X_1 \cap X_2 \cap X_3\right) \cup \left(X_1 \cap \overline{X_2} \cap \overline{X_3}\right) \cup \\ \cup \left(\overline{X_1} \cap X_2 \cap \overline{X_3}\right) \cup \left(\overline{X_1} \cap \overline{X_2} \cap X_3\right), \quad (11)$$

where $\cup$, $\cap$, $\bar{X}$ – respectively symbols of conjunction, disjunction and negation.

The minimized Boolean functions for various bolted modes are:

– the normal mode of operation corresponds to the evaluation function:

$$F_{n.m} = \left(X_1 \cap \overline{X_2} \cap \overline{X_3}\right) = (1,0,0); \quad (12)$$

– the appearance of the initial moment of BCJ weakening corresponds to the evaluation function:

$$F_{w.bj.} = \left(X_1 \cap X_2 \cap \overline{X_3}\right) = (1,1,0); \quad (13)$$

– the onset of fault mode, leading to the EE shutdown, corresponds to the evaluation function of the form:

$$F_{f.m.} = \left(X_1 \cap X_2 \cap X_3\right) = (1,1,1). \quad (14)$$

To construct diagnostic tests for detecting the initial moment of BCJ weakening for stationary and deterministic current and ambient temperature modes, let's introduce additional arguments for Boolean variables:

– X_4 – «0» – when the condition $dI_n/dt \neq 0$ is met;
– X_4 – «1»–» – when the condition $dI_n/dt = 0$ is met;

– X_5 – «0»–» – when the condition $dT_a/dt \neq 0$ is met;
– X_5 – «1»–» – when the condition $dT_a/dt = 0$ is met;
– X_6 – «0»–» – when the condition $dT_{bj}/dt \neq 0$ is met;
– X_6 – «1»–» – when the condition $dT_{bj}/dt = 0$ is met.

The expression of six variables in PDNF has $2^{2^6} = 64536$ components.

Using the minimized disjunctive Boolean functions of the modes to determine the BCJ fault-free and faulty states, let's obtain the expressions:

– the onset of the initial moment of BCJ weakening corresponds to the function:

$$F_{w.bj.} = \left(X_1 \cap X_2 \cap \overline{X_3}\right) \sim \left(X_4 \cap X_5 \cap X_6\right) = (1,1,0,1,1,1); \quad (15)$$

– the onset of faulty mode, which determines the moment of EE disconnection from the network, corresponds to Boolean variable of the form:

$$F_{f.m.} = \left(X_1 \cap X_2 \cap X_3\right) \sim \left(X_4 \cap X_5 \cap X_6\right) = (1,1,1,1,1,1); \quad (16)$$

where ~ – the equivalence symbol.

To construct diagnostic tests for detecting the initial moment of BCJ weakening for the random and deterministic current mode and ambient temperature, the following arguments will be added to the Boolean variables:

– X_4 – «0» – when the condition $M_{I,i} - M_{I,i+1} \neq 0$ is met;
– X_4 – «1» – when the condition $M_{I,i} - M_{I,i+1} = 0$ is met;
– X_5 – «0» – when the condition $M_{Ta,i} - M_{Ta,i+1} \neq 0$ is met;
– X_5 – «1» – when the condition $M_{Ta,i} - M_{Ta,i+1} = 0$ is met;
– X_6 – «0» – when the condition $M_{Tbj,i} - M_{Tbj,i+1} \neq 0$ is met;
– X_6 – «1» – when the condition $M_{Tbj,i} - M_{Tbj,i+1} = 0$ is met.

Estimated Boolean functions of detecting the initial moment of BCJ weakening and emergency modes in case of random changes in current will be determined by the expressions:

– the onset of the initial moment of BCJ weakening corresponds to the function:

$$F_{w.bj.} = \left(X_1 \cap X_2 \cap \overline{X_3}\right) \sim \left(X_4 \cap X_5 \cap X_6\right) = (1,1,0,1,1,1); \quad (17)$$

– the onset of emergency mode, which leads to the EE shutdown from the mains corresponds to the function:

$$F_{e.m.} = \left(X_1 \cap X_2 \cap X_3\right) \sim \left(X_4 \cap X_5 \cap X_6\right) = (1,1,1,1,1,1). \quad (18)$$

Taking into account the load current modes and the ambient air temperature makes it possible to increase the accuracy of detecting the pre-emergency situation and avoid pre-fault of the EE protection system while BCJ weakening.

7. SWOT analysis of research results

Strengths. Taking into account mode changes in the load current and the temperature of air around BCJ allows to increase the sensitivity of the device when detecting a pre-emergency situation and to avoid false disconnections of equipment. Timely detection of the initial moment of BCJ weakening allows service personnel to plan maintenance work without emergency shutdowns of the equipment.

Weaknesses. The use of developed devices increases the cost of equipment protection.

Opportunities. The use of the developed devices and algorithms for diagnosing the state of BCJ help to avoid damage from emergency response, equipment downtime and the shortfall of finished products. The use of the developed devices, for example in medical institutions for the protection of X-ray machines, makes it possible to prevent additional adverse effects on the patient during the examination.

Threats. The investigated analogues of the devices for diagnostics and protection of electrical equipment, carried out by the author, and the expert opinion of the Institute of Intellectual Property of Ukraine, when issuing patents for the invention, did not reveal similar world devices that perform newly developed functions.

8. Conclusions

1. The analysis of the causes of the false triggering of the device to detect the initial moment of BCJ weakening is carried out. This analysis show that under conditions of non-stationary and random modes of load current, mains voltage and ambient temperature, these reasons are related to the duration of the transient heating of the bolted current-carrying joint. Therefore, the improvement of the thermal method of non-destructive testing consists in the fact that the diagnosis of the initial moment of BCJ weakening is carried out in the areas of stationarity strictly defined by the developed requirements.

2. It is shown that for constructing diagnostic tests for detecting the initial moment of BCJ weakening, it is advisable to use the arguments of Boolean variables and minimized disjunctive functions. This makes it possible to simplify the algorithm and computer program, and also increased the speed of diagnostic and protection devices by 5–7 %.

References

1. Kriterii diagnostiki vintovykh soedineniy v ul'trazvukovoy tomograficheskoy apparature / Krivonosov V. E. et. al. // Visnik Khmel'nits'kogo natsional'nogo universitetu. Seriya: Tekhnichni nauki. 2017. Issue 1. P. 52–57.
2. Sposib kontroliu za stanom boltovykh ziednan elektroobladnannia, shcho pratsiuie zi zminnym navantazhenniam: Pat. No. 107749 UA. MPK: G01N 27/24, H02K 15/12, G01N 25/72, H02H 5/04, H01R 31/00, G01N 27/20, G01R 13/00 / Kryvonosov V. E. No. a 201309491; declareted: 29.07.2013; published: 10.02.2015; Bul. No. 3. 4 p.
3. Brady J. Thermal Patterns Associated with Infrared Inspection of Electrical Systems. 2011. URL: https://www.irinfo.org/05-01-2011-brady/
4. Izmaylov V. V., Naumov A. E. Avtomatizirovannaya sistema prognozirovaniya ostatochnogo resursa elektrokontaktnykh soedineniy // Programmnye produkty i sistemy. 2008. Issue 2. P. 73–75.
5. A guide to low resistance testing. 2017. URL: https://www.techrentals.com.au/pdf_files/Megger_A_20Guide_20to_20Low_20Resistance_20Testing.pdf
6. Ustroystvo dlya kontrolya temperatury kontaktnykh soedineniy v ustroystvakh, nakhodyashhimsya pod vysokim napryazheniem: Pat. No. 2408120 RU. MPK: H02H5/04 / Kaplya N. G., Kaplya E. N. No. 2009115534/07; declareted: 24.04.2009; published: 27.12.2010; Bul. No. 36. 5 p.
7. Genutis D. A. Infrared Inspections and Applications // NETA WORLD Winter. 2006–2007. URL: https://studylib.net/doc/18260220/infrared-inspections-and-applications
8. Electrical heating tube detection device: Pat. No. CN 102636686 A. 15.08.2012. URL: https://patents.google.com/patent/CN203526081U/en

9. Prystrii avtomatychnoho monitorynhu stanu kontaktnykh ziednan vysokovoltnykh pidstantsii i linii elektroperedach: Pat. No. 104546 UA. MPK: H02H 5/04, H02G 15/12, H01R 13/02, H02G 15/08, G05B 19/05 / Teslia Yu. A., Diachenko M. D. No. a201301914; declareted: 18.02.2013; published: 10.02.2014, Bul. No. 3.
10. Dynamic Thermal Mapping: Pat. No. 13/689340 USA. MPK: 702/64, 361/689 / Kennedy R., Hope J. No. 20130138371; declareted: 29.11.2012; published: 30.05.2013.
11. Prystrii diahnostuvannia oslablennia boltovykh strumoveduchykh ziednan i obryvu strumoveduchykh chastyn systemy elektropostachannia elektropryimacha: Pat. No. 127922 UA. MPK: H02H 5/04, H02K 15/12 / Kryvonosov V. E., Pirotti Ye. L. No. u201802711_2; declareted: 19.03.2018; published: 27.08.2018; Bul. No. 16. 4 p.
12. Chistyakov V. I. Kurs teorii veroyatnosti. Moscow, 1978. 224 p.

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