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141 ЕЛЕКТРОЕНЕРГЕТИКА, ЕЛЕКТРОТЕХНІКА ТА ЕЛЕКТРОМЕХАНІКА

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ANALYSIS AND CONCEPT OF DEVELOPMENT OF NON-DESTRUCTIVE TEST METHODS FOR DIAGNOSING ELECTRIC MOTOR INSULATION

The timely detection of a critical state and forecasting the development of an emergency situation in the insulation of AM (asynchronous motor) windings is the main direction of increasing the economic efficiency of electrical engineering systems. One of the methods of reducing electricity losses is the compensation of reactive power, both complex and local. Asynchronous motors consume more than 60% of the produced electricity. Modern microprocessor devices, which are implemented in the automation of electrical engineering complexes, enable to combine local compensation of the reactive power consumed by synchronous motors with a diagnostic system for monitoring and predicting the residual life of an asynchronous motor and detecting a winding circuit in the stator windings of an electric motor. The purpose of the work is the analysis of the existing non-destructive test methods for diagnosing the state of the dielectric property of the insulation of AM windings, substantiating the direction of the development of diagnostic test methods and forecasting the decrease in the property of the body insulation of AM windings with the use of residual energy in the conditions of using a capacitor bank. To achieve the goal, the following tasks were solved: an analysis of the control methods of body and turn insulation was conducted; for the first time, the energy remaining in the capacitors after their disconnection was used in non-destructive test methods; it was proven that to predict the residual resource of the motor housing insulation, the time constant of the capacitor discharge decay can be effectively used as a criterion parameter, similarly, to detect a short circuit in the stator windings, the periodic voltage decay time on the capacitor can serve as a useful criterion; established interrelationships between changes in the resistance of the casing insulation of the windings and the time constant of the capacitor discharge. The most important result is the establishment of a unique relationship between the state of the case insulation and the value of the voltage decay time constant on the capacitor; change in period time and the number of turned-off turns in the AM stator winding. The most significant result is that the change in the time constant was used for the first time as a criterion parameter for predicting the residual life of the dielectric properties of the motor body insulation, and the change in the time period as a criterion parameter for the detection of a winding circuit. The significance of the study is that the value obtained after the first disconnection of the

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electric motor from the network is taken as the basic value of the constant decay time. Methods have been proposed and software developed for the device, which allows monitoring non-phase voltage modes of the network and current circuits during the operation of the electric motor, and when the electric motor is disconnected from the network – to control the value of the insulation resistance of the stator windings of the electric motor and the cable, as well as to predict the residual life of the electric motor.
Keywords: *corpus insulation of electric motor windings, forecasting, residual resource, local compensation of reactive power, discharge time constant, capacitor, software, windings of electric motor stator windings, transient processes, test diagnostics.*

Кривоносов В.Є., Матвієнко О.М., Кривоносов В.В., Пруднікова Н.Д., Савенко О.С., Скосирєв В.Г. Аналіз та концепція розвитку неруйнівних тестових методів діагностування ізоляції електродвигуна*. Умови роботи асинхронного двигуна (АД) пов'язані з неякісною напругою мережі живлення, підвищеною запиленістю, вологістю та кислотністю навколишнього середовища, технологічними та випадковими струмовими перенавантаженнями, що є наслідком зниження властивості ізоляції та непередбачених аварійних ситуацій. Щорічно до 80% аварійного виходу АД з ладу припадає на пошкодження ізоляції як корпусної до 20-25%, так і міжвиткової, на долю якої випадає до 80%. Своєчасне виявлення критичного стану і прогнозування розвитку аварійної ситуації ізоляції обмоток АД є головним напрямком підвищення економічної ефективності електротехнічних комплексів. Одним з методів зниження втрат електроенергії є компенсація реактивної потужності як комплексна, так і локальна. Асинхронні двигуни споживають більше 60% вироблюваної електроенергії. Застосування асинхронних двигунів у нерегульованому електроприводі складає до 75% від усього парку електроприводу. Щорічно аварійний вихід з експлуатації АД становить до 20-25%, а в деяких випадках – до 30%. Сучасні мікропроцесорні пристрої, які впроваджуються в автоматизацію електротехнічних комплексів, дозволили поєднати локальну компенсацію реактивної потужності, що споживають асинхронні двигуни, з діагностичною системою контролю та прогнозування залишкового ресурсу роботи асинхронного двигуна та виявлення виткового замикання у статорних обмотках електродвигуна. Метою роботи є аналіз існуючих тестових неруйнівних методів діагностування стану діелектричної властивості ізоляції обмоток АД, обґрунтування напрямку розвитку методів тестової діагностики та прогнозування зниження властивості корпусної ізоляції обмоток АД із застосуванням залишкової енергій в умовах використання батареї конденсаторів. Для досягнення мети вирішені такі завдання: проведено аналіз методів контролю корпусної та виткової ізоляцій; вперше енергію, яка залишається в конденсаторах після їх відключення, використано в тестових неруйнівних методах; доведено, що для прогнозування залишкового ресурсу корпусної ізоляції електродвигуна в якості критеріального параметру доцільно використовувати постійну часу затухання розряду конденсатора, а для виявлення виткового замикання в статорних обмотках в якості критеріального параметра доцільно використовувати час періоду періодичного затухання напруги на конденсаторі; встановлені взаємозв'язки зміни опору корпусної ізоляції обмоток та постійною часу розряду конденсатора. Найважливішим результатом є встановлення однозначного взаємозв'язку стану корпусної ізоляції та величини постійної часу згасання напруги на конденсаторі; зміна часу періоду та кількості вимкнутих витків у статорній обмотці АД. Найбільш суттєвим результатом є те, що зміну постійної часу вперше використано як критеріальний параметр для прогнозування залишкового ресурсу діелектричних властивостей корпусної ізоляції електродвигуна, а зміну часу періоду – як критеріальний параметр виявлення виткового замикання. Значимістю дослідження є те, що базовим значенням постійної часу згасання приймається значення, отримане після першого відключення електродвигуна від мережі. Запропоновано методи і розроблено програмне забезпечення для пристрою, що дозволяє контролювати неповнофазні режими* *напруги мережі та струмових ланцюгів в період роботи електродвигуна, а при відключенні електродвигуна від мережі – контролювати величину опору ізоляції статорних обмоток електродвигуна і кабелю, а також прогнозувати залишковий ресурс експлуатації електродвигуна.*

Ключові слова: *корпусна ізоляція обмоток електродвигуна, прогнозування, залишковий ресурс, локальна компенсація реактивної потужності, постійна часу розряду, конденсатор, програмне забезпечення, виткові замикання статорних обмоток електродвигуна, перехідні процеси, тестова діагностика.*

Description of the problem. Over 80% of the total amount of electrical equipment of electric drives of electrotechnical complexes of industrial and agro-industrial enterprises are asynchronous motors (AM) with a short-circuited rotor [1]. These motors often operate under harsh conditions, including low-quality voltage of the power supply network, increased dustiness, humidity and acidity of the environment, technological and accidental current overloads, which is a consequence of the reduction of insulation properties and unforeseen emergency situations [2, 3]. Every year, up to 80% of the emergency failure of AS occurs due to damage to the insulation, both body insulation up to 20-25%, and inter-turn insulation, which accounts for up to 80% [4]. Timely detection of a critical state and forecasting the development of an emergency situation of insulation of AM windings is the main direction of increasing the economic efficiency of electrotechnical complexes.

Assessing the technical condition of AM is critical for improving the reliability and trouble-free operation of electrical systems.

A promising direction for assessing the insulation condition of AM windings is the development of test diagnostics using capacitor battery energies.

In works [5, 6] it was proved that with local compensation of reactive power, by connecting a battery of capacitors in parallel with the AM, the energy that remained in the capacitors after they were turned off was used to assess the condition of the casing insulation of the AM windings [7]. The energy of the capacitors is used in relay protection to power switches, as well as to improve the starting characteristics of AM [8].

Timely diagnostics of AM conditions can significantly reduce repair costs and loss of working time of service personnel associated with unplanned repairs and stoppages of technological processes.

Thus, the development of new non-destructive methods of controlling damage to the body and inter-turn insulation, without taking AM out of operation, with the use of energy-saving approaches, is an urgent task at the present time, which will increase the reliability of electrotechnical complexes (ETC) and avoid economic losses.

Analysis of the latest research and publications. In terms of economic expediency, a number of industrial enterprises are forced to switch from a system of planned and preventive repairs to repairs and prevention upon detection before an emergency situation. During maintenance according to the actual condition, the normal operation of the AM is not disturbed due to human intervention. Currently, the development of methods and means of monitoring the current condition of engines allows the implementation of maintenance technology based on the actual condition [9].

As a rule, the assessment of the state of insulation of the stator windings of AM is carried out during technological pauses.

There are various methods of detecting damage to the AM insulation. A diagnostic method based on the analysis of the deformed magnetic field in the gap of the machine [10] or based on the method of compensation of the field in the air gap is used to detect damage to the turn insulation in the AM windings. It is shown that when the number of closed turns increases, the ampere-turns in these turns increase, accordingly, the intensity of the magnetic field in the air gap also increases. The application of the estimate of the reverse magnetic field, which occurs as a result of the turn shorting, is inefficient for a small number of closed turns in multi-turn windings.

In the works of the authors [11], a method of determining the inter-turn short circuit was developed, in which the shift between the angles of phase currents and phase voltages during the operation of AM is controlled. This additional diagnostic parameter controls the asymmetric modes in the AM stator winding. But in this work, there is no study of the influence of the asymmetry of the phase voltage of the power supply network on the sensitivity of detecting the number of closed turns.

In work [12], the authors applied vector analysis when detecting the initial occurrence of a winding circuit taking into account the asymmetry of the voltage in the power supply network, but with a dynamic change in the asymmetry the voltage of the power supply network, the reliability of detecting the initial moment of the appearance of a winding circuit decrease.

In works [13], the method and devices for detecting a winding circuit using the coefficients of asymmetry of phase currents and the coefficient of asymmetry of the voltage of the power supply network are presented.

In work [14], the most widely used test method for monitoring the body and turn insulation in the windings of a non-working electric motor is described - it is the millivoltmeter and ammeter method.

In work [15], the authors considered test tests of inter-turn and body insulation of a non-working electric motor. An impulse voltage of 1000V-2500V is applied to the phase windings, signals are recorded in the form of the amplitude value of the voltage from each of the windings of the electric motor. Signals are compared during tests of two windings, the information is processed by the Proni method.

The disadvantages of the method are that it is used during tests of a non-working electric motor, requires a separate high-voltage power source, to ensure sufficient sensitivity requires N - the number of samples during the test, and does not take into account the discrepancy in the parameters of the electric motor windings [16].

In the work of the authors Jameson N.J., Azarian M.H., Pecht M. [17] a method for detecting the degradation of insulation used in low-voltage devices by evaluating the change in the impedance characteristic is presented. It is shown that the impedance of the coil changes differently under different load conditions, which reflects signs of insulation deterioration due to different damage mechanisms. This method can be used to estimate the insulation life of electromagnetic coils during preventive maintenance.

Existing diagnostic methods for monitoring the occurrence of pre- and emergency situations require additional equipment and do not always have sufficient sensitivity. In known scientific works, it is not enough to consider the methods of non-destructive test diagnostics of control and forecasting of the decrease in the property of case insulation from the use of technological equipment, for example, static compensators of reactive power. The development of new methods allows to automate the monitoring of the condition of the housing insulation of electric motors

Purpose and task statement. Analysis of existing non-destructive test methods for diagnosing the state of the dielectric property of insulation of AM windings, substantiation of the direction of development of diagnostic test methods and forecasting the decrease in the properties of body and turn insulation of AM windings with the use of residual energy in the conditions of using a capacitor bank.

Methods. The electrical method of the influence of the voltage of the charged capacitor U_c on the change of the functional parameters of the transient process and the integral analysis of the dependence $U_c = f(\tau)$, periodic and aperiodic components of the voltage decrease on the capacitor in time – τ.

Summary of the main material. Winding insulation by the method of non-destructive test diagnostics is based on the formation of artificial disturbances on the body insulation and windings of AM during the technological pause and the analysis of the functional parameters of the transition process.

According to the electrical scheme of the discharge of the capacitor on the active-inductive resistance (fig. 1).

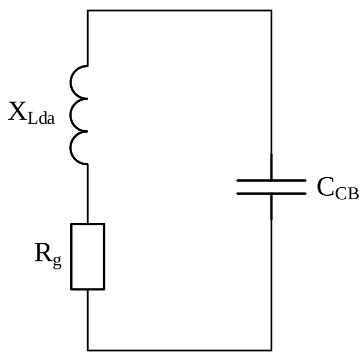

Fig. 1 – Electric scheme of the discharge of the capacitor on the active-inductive resistance

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The equation of the voltage change at the capacitor terminals was analyzed

$$E = I \cdot R_g - U_{CB} \, , \tag{1}$$

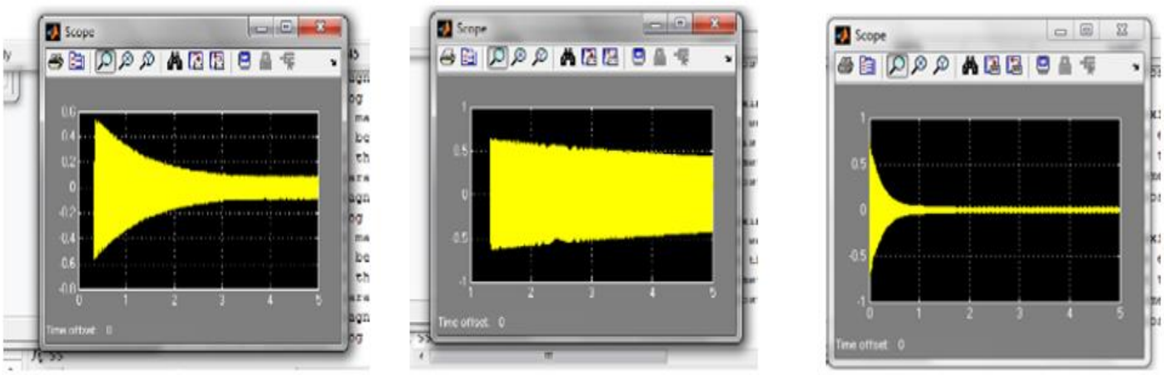
$$\frac{d^2 I}{dt^2} + \frac{R_g}{L_{da}} \frac{dI}{dt} + \frac{I}{L_{da} \cdot C_{CB}} = 0 \, , \tag{2}$$

where X_{Lda} – inductive resistance of the stator winding AM, R_g – active resistance of the stator winding or body insulation AM, R_g, X_g – active and capacitive components of cable line insulation resistance and AL, C_{CB} – capacity of a capacitor bank (CB) with residual voltage after its disconnection from the network.

The solution of this equation is known and given in [17].

The nature of the transient process occurring in the circuit depends on the ratio of the resistance parameters of the active and inductive components.

The results of mathematical modeling shown in fig. 2, made it possible to establish the numerical values of the CB discharge speed and to develop an energy-saving method and device for diagnosing the power supply network in operating mode and the state of the case insulation when the AM is disconnected [18, 19], which use the energy that remained in the capacitor after it was disconnected from the power supply network.



a) b) c)

Fig. 2 – Simulation results: a) the discharge rate is 0.1 v/s; b) the discharge rate is 0.5 v/s, c) the discharge rate is 0.01 v/s

Figure 3 shows a structural model of information support for assessing the quality of insulation and power supply network modes with local compensation of reactive power.

1. In AM operating mode, local compensation of reactive power is carried out and changes in phase voltage values are measured at the CB terminals, in the absence of one- or two-phase voltages, the presence of incomplete phase modes or short circuits in the power network is determined.

2. At the moment of disconnection of AM from the network, the maximum value of the voltage at the terminals of one of the capacitors is determined. The capacitor with the highest voltage is connected to the «phase-body» terminals of the AM and the CB discharge rate is measured on the resistance of the body insulation. Different values of the rate of change of voltage at the capacitor terminals correspond to different values of the insulation resistances of AM.

The development of this test method made it possible to develop a method and a device for diagnosing and predicting a decrease in the property of the body insulation of the stator windings of AM [20, 21].

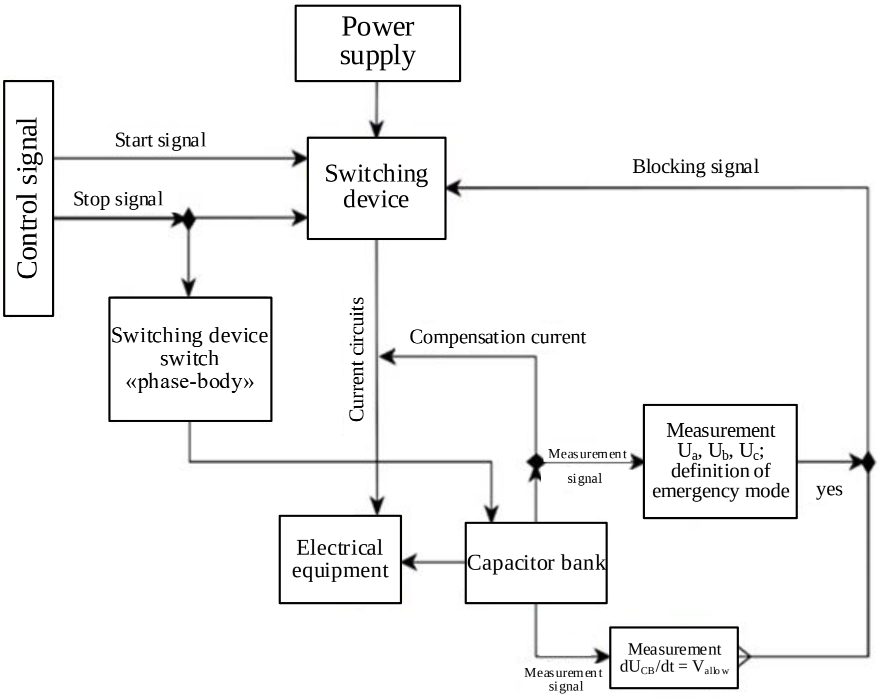


Fig. 3 – Structural model of information support for assessing the quality of insulation and power network modes with local compensation of reactive power

The method consists in the possibility of predicting the remaining service life of AM. The scheme of the laboratory installation, presented in Figure 4, allows to analyze the transient processes of the capacitor discharge in the circuit «complex resistance of the AM winding + capacitor capacity + complex resistance of the housing insulation».

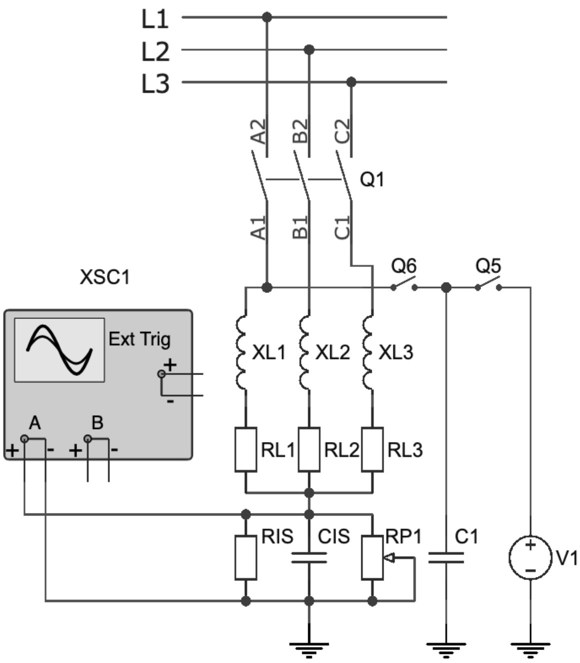


Fig. 4 – Schematic electrical diagram used for simulation and research of transient processes

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R_{is}, C_{is} represent the active and capacitive components of the replacement model of the AM case insulation. R_{P1} – variable resistance, which allows to simulate changes in the dielectric properties of insulation. *XSC1* represents an oscilloscope and is a DC power source.

The change in voltage on the body insulation of AM according to (1) and (2) is described by the expression:

$$U_{Z_{is}} = U_{C_1}\left(1 - e^{-\frac{t}{\tau_{Rr}}}\right), \tag{3}$$

where τ_{Rr} – time constant of over-damping discharge $\tau_{Rr} = C_1 R_{is}$ and depends on the value of the active component of the complex insulation resistance.

U_{C_1} represents the voltage at the terminals of the phase capacitor.

The decay time of the aperiodic capacitor discharge process depends on the active component of the resistance of the body insulation and the following inequality is fulfilled:

$$\tau_a > \tau_b > \tau_c \leftrightarrow R_a > R_b > R_c, \tag{4}$$

where τ_a, τ_b, τ_c and R_a, R_b, R_c are time constants and active components of the resistance reduction of the body insulation AM, respectively.

Inequality (4) allows considering the capacitor discharge time constants as a critical parameter for assessing the state of the dielectric properties of the insulation.

The intensity of the decrease in the dielectric properties of the insulation is characterized by the parameter «rate of change of time constants» of capacitor discharges during engine operation, which is determined by the expression:

$$V_{disc\ i} = \frac{\tau_{first} - \tau_i}{\sum_i^n \Delta t_i}, \tag{5}$$

where τ_{first} is the initial capacitor discharge time when the engine is first disconnected from the power source;

τ_i – the capacitor discharge time constant during current disconnections of the engine from the power source;

Δt_i – engine operation time in the current period;

n – the number of periods of engine operation.

Approbation of the method.

The first disconnection of AM from the power supply network, during which is determined $t_{disc\ 1}$ – the initial capacitor discharge time, τ_{first} – the initial capacitor discharge time constant at the initial dielectric properties of the insulation of the AM stator windings, τ_{crist} – the critical value of the capacitor discharge time constant, at the insulation resistance, $R_{1S} = 0.5\ MOhm$.

During the first disconnection of AM from the resistance network, the resistance R_{P1} is disconnected. Using the Start button Q_5, connect a capacitor (for example, a capacitor C_1) to the power supply unit V_1, the voltage is 150 V. In this way, we simulate the charge of the capacitor C_1, we consider it charged to the highest voltage. Using the Start button Q_6 connect the charged capacitor to the «phase + body» terminals of AM. Fig. 5 shows a graph of the voltage change during the discharge of capacitor C_1.

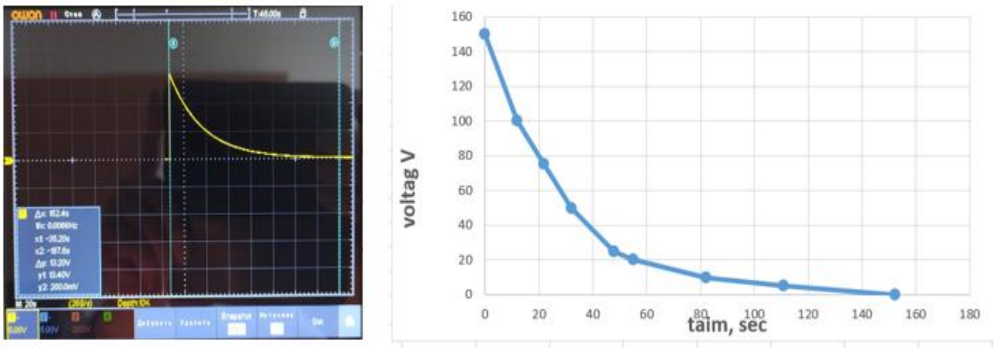

Fig. 5 – Graph of voltage change during capacitor discharge C_1: $t_{disc1} = 152.4\ sec$; $\tau_{first} = {}^{152.4}/_{5} = 30.5\ sec$

The initial insulation resistance of the AM stator windings, without taking into account the divider coefficient in the voltage measurement circuit, is equal to:

$$R_{1S\,first} = \frac{\tau_{first}}{C_1} = 10.2\ MOhm.$$

We calculate τ_{crit} – the critical value of the capacitor discharge time constant $\tau_{crit} = 1.5\ sec$.

The second disconnection of AM from the power supply network. Resistance $R_{P2} = 20\ MOhm$. We assume that during operation of AM the insulation resistance has decreased and is equal to:

$$R_{1S\,2} = \frac{R_{1S\,first} \cdot R_{P2}}{R_{1S\,first} + R_{P2}} = 6.6\ MOhm.$$

Consequently, the level of dielectric properties of the insulation decreased by 36%. Suppose that the operating time of the electric motor was $\Delta t_2 = 10\ hours$. In fig. 6, a graph of voltage changes during capacitor discharge is given.

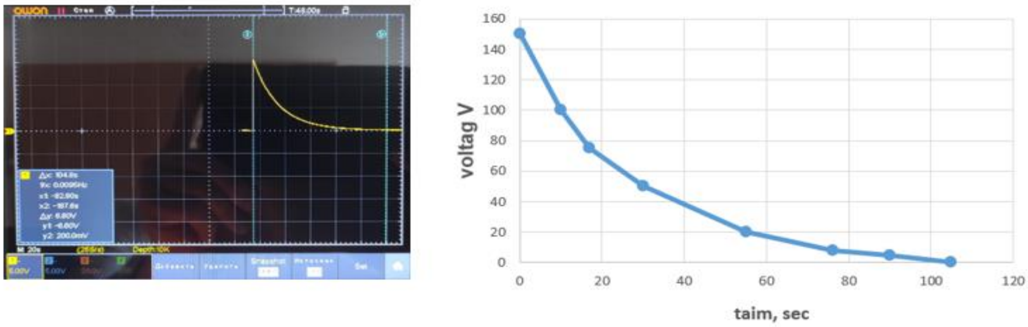

Fig. 6 – Graph of voltage change during capacitor C_1 discharge: $t_{disc2} = 104.8\ sec$; $\tau_{disc2} = 20.9\ sec$

The rate of change of the capacitor discharge time constant after the second period of AM operation.

The predicted remaining operating time of AM is equal to:

$$T_{disc} = \frac{20.9 - 1.5}{0.27 \cdot 10^{-3}} = 71.9 \cdot 10^3 = 19.97\ hours.$$

Thus, if the wear, i.e. deterioration of the insulation properties, will occur at this rate, the AM will work for another 19.97 hours.

The remaining service life of the electric motor in percent as:

$$Rr_{disct} = \left(1 - \frac{30.5 - 20.9}{30.5 - 1.5}\right) \cdot 100\% = 77\%.$$

The third disconnection of AM from the power supply network. Resistance $R_{P3} = 5\ MOhm$. We assume that during the operation of AM the insulation resistance has decreased and is equal to:

$$R_{1S\,3} = \frac{R_{1S\,first} \cdot R_{P3}}{R_{1S\,first} + R_{P3}} = 6.6\ MOhm.$$

Therefore, the level of dielectric properties of the insulation decreased by 70%. We calculate that the working time of AM was $\Delta t_3 = 30\ hours$. Fig. 7 shows a graph of voltage changes during capacitor C_1 discharge.

The rate of change of the capacitor discharge time constant after the third period of AM operation:

$$V_{disc3} = \frac{20.9 - 10.82}{(10 + 30) \cdot 60 \cdot 60} = 7.5 \cdot 10^{-5}.$$

We adjust the remaining working time of AM, which is equal to:

$$T_{disct} = \frac{10.82 - 1.5}{7.5 \cdot 10^{-5}} = 1.242 \cdot 10^5 = 34.5\ hours.$$

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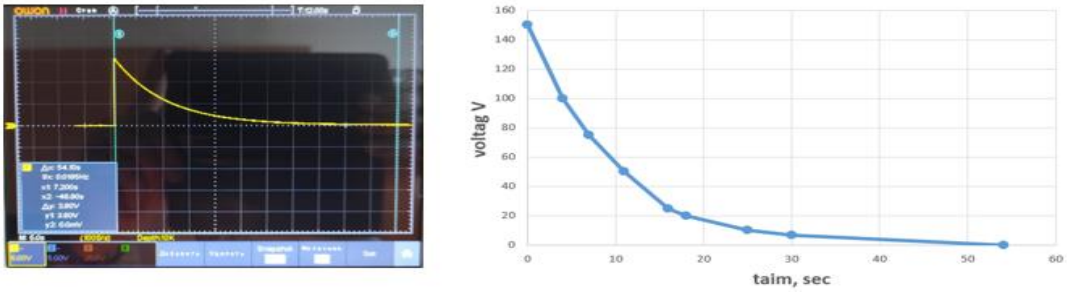

Fig. 7 – Graph of voltage change during capacitor C_1 discharge: $t_{disc3} = 54.1\ sec$; $\tau_{disc3} = 10.82\ sec$

Thus, if the deterioration of the insulation properties will occur at this rate, the AM will work for another 34.5 hours.

The remaining service life of the electric motor in percent as:

$$Rr_{disct} = \left(1 - \frac{30.5 - 10.82}{30.5 - 1.5}\right) \cdot 100\% = 33\%.$$

The fourth disconnection of AM from the power supply network. Resistance $R_{P4} = 0.3\ MOhm$. We assume that during the operation of AM the insulation resistance has disappeared and is equal to:

$$R_{1S\,4} = \frac{R_{1S\,first} \cdot R_{P4}}{R_{1S\,first} + R_{P4}} = 0.292\ MOhm.$$

Therefore, the level of dielectric properties of the insulation has decreased by 100% and further operation of the AM will lead to an accident. Let's assume that the working time of AM was $\Delta t_4 = 80\ hours$. Fig. 8 shows a graph of voltage changes during capacitor C_1 discharge.

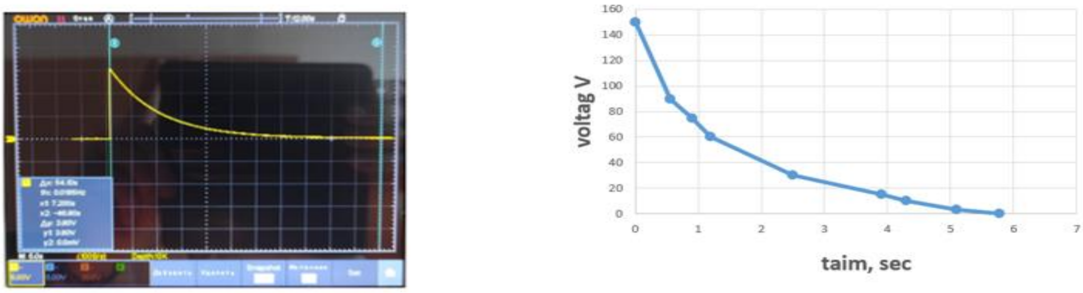

Fig. 8 – Graph of voltage change during capacitor C_1 discharge: $t_{disc4} = 5.7\ sec$; $\tau_{disc4} = 1.14\ sec$

The rate of change of the capacitor discharge time constant after the fourth period of AM operation:

$$V_{disc4} = \frac{20.9 - 1.14}{(10 + 30 + 80) \cdot 60 \cdot 60} = 4.07 \cdot 10^{-6}.$$

We adjust the remaining working time of AM is equal to:

$$T_{disct} = \frac{10.82 - 1.5}{4.07 \cdot 10^{-6}} = 2.3 \cdot 10^{6} = 0.0083\ hours \approx 0.$$

Thus, with an error of up to 1%, it can be stated that the dielectric properties of the AM stator winding insulation are exhausted, and the AM requires repair. The remaining service life of the electric motor in percent as:

$$Rr_{disct} = \left(1 - \frac{30.5 - 1.14}{30.5 - 1.14}\right) \cdot 100\% = 0\%.$$

Prospects for the development of a non-destructive testing method for detecting a winding circuit using the energy that remained in the capacitors.

The analysis of expression (1) made it possible to consider the periodic process of reducing the voltage on the capacitor terminals for testing the winding circuit in the stator windings of AM.

Study of the transient process of the capacitor discharge on the resistance of the AM winding, the connection scheme of the stator windings «star with neutral point» is shown in Fig. 9.

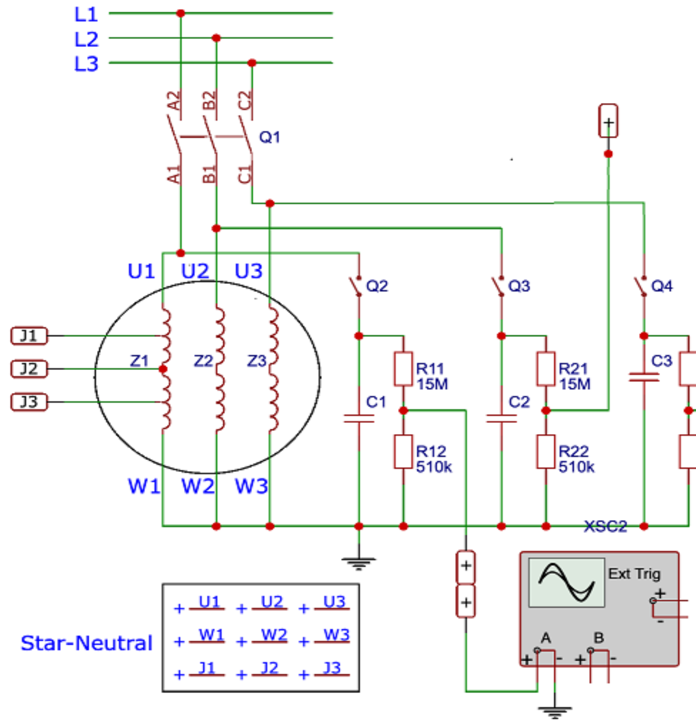

Fig. 9 – Single-line electrical circuit to investigate damage in AM with the winding connection as «star with neutral point»: u_1, u_2, u_1 – beginning of windings; w_1, w_2, w_3 – the end of the windings; j_1, j_2, j_3 – branching of the oscilloscope in the winding of phase «A»; Z_1, Z_2, Z_3 – complex winding supports

According to the differential equation (1), the nature of the transient process occurring in the circuit depends on the ratio of the parameters C, R_{Li}, L_i and has a periodically decaying character, and has a solution

$$q(t) = A_0 \cdot e^{-R_{Li}t/2L_i} \cdot \sin(\omega t + \alpha_0), \quad (6)$$

$$\omega = \sqrt{\frac{1}{L_i \cdot C_i} - \frac{{R_{Li}}^2}{4{L_i}^2}}, \quad (7)$$

$$\tau = \frac{2\pi}{\sqrt{\frac{1}{L_i \cdot C_i} - \frac{{R_{Li}}^2}{4{L_i}^2}}}, \quad (8)$$

where ω – oscillation frequency of the contour, A_0 – amplitude of oscillations, α_0 – phase, τ – the time of the transition period, q – the electric charge on the capacitor plates, R_{Li} – the active component of the resistance of the AM winding and the power cable, L_i – inductance of AM winding, C_i – phase capacity of the capacitor bank.

The decrement of damping of oscillations in the circuit is determined by the formula:

$$\beta = \frac{R_{Li}}{2L_i}. \quad (9)$$

Instantaneous amplitudes of capacitor charge fluctuations:

$$A = A_0 \cdot e^{-\frac{tR_{Li}}{2L_i}} = A_0 \cdot e^{-\beta t}. \quad (10)$$

The change in voltage over time at the capacitor terminals will be determined as:

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$$U_{ci} = U_0 \cdot e^{-R_{Li}t/2L_i} \cdot \sin(\omega t + \alpha_0).$$

The initial phase of oscillations α_0 is determined by the expression

$$\alpha_0 = arctg\sqrt{\frac{4L_i}{C_i \cdot R_{Li}^2} - 1}. \quad (11)$$

The initial voltage amplitude U_0 corresponds to the value of the voltage at the terminals of the phase capacitor when it is turned off from the power supply, while $\alpha_0 = 90°$.

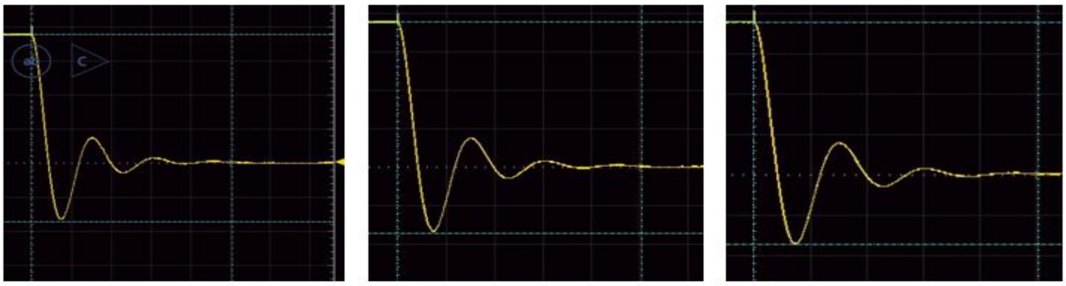
The method of monitoring the state of inter-turn insulation, according to [22], is carried out as follows.

Before stopping AM with the switch Q_1, according to the needs of the technology, the phase capacitors are turned off with the switches Q_2, Q_4, Q_3 (Fig. 9) provided that each phase capacitor is disconnected separately, when a positive amplitude value of the power supply network is reached at its terminals, thus the equation is fulfilled:

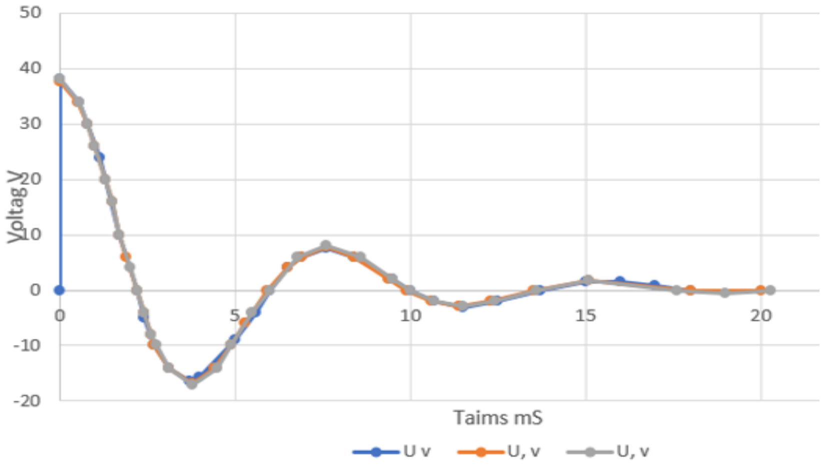
$$U_{c1} = U_{c2} = U_{c3}.$$

After the AM is completely stopped, the capacitors C_1, C_2, C_3 are alternately connected to the AM phase windings.

In fig. 10 presents oscillograms of voltage changes at the terminals of phase capacitors.



a) b) c)



U v – the curve corresponds to the oscillogram a) C_1 connected to the terminals u_1-w_1
U, v – the curve corresponds to the oscillogram b) C_2 connected to the terminals u_2-w_2
U, v – the curve corresponds to the oscillogram c) C_3 connected to the terminals u_3-w_3

Fig. 10 – Oscillograms and graphs of voltage changes at the terminals of phase capacitors

Running of the curves on the graph of fig. 10, related to the discrepancy in the design parameters of the resistances of the phase windings. As a diagnostic criterion, it is possible to apply the integral coefficient K_{In} defined by the expression:

$$K_{In} = \int_0^{t_{fi}} (U_0 \cdot e^{-R_{Li}t/2L_i} \cdot \sin(\omega t + \alpha_0))dt, \quad (12)$$

where t_{fi} – the transition time.

The error associated with the discrepancy in the design parameters of the resistances of the phase windings will be determined as:

$$\Delta K_{In} = K_{Ina} - K_{Inb}. \quad (13)$$

Fig. 11 shows graphs of the voltage changes at the capacitor terminals (u_1-w_1) when the ΔW windings are turned off. Connection scheme of windings «star with 0».

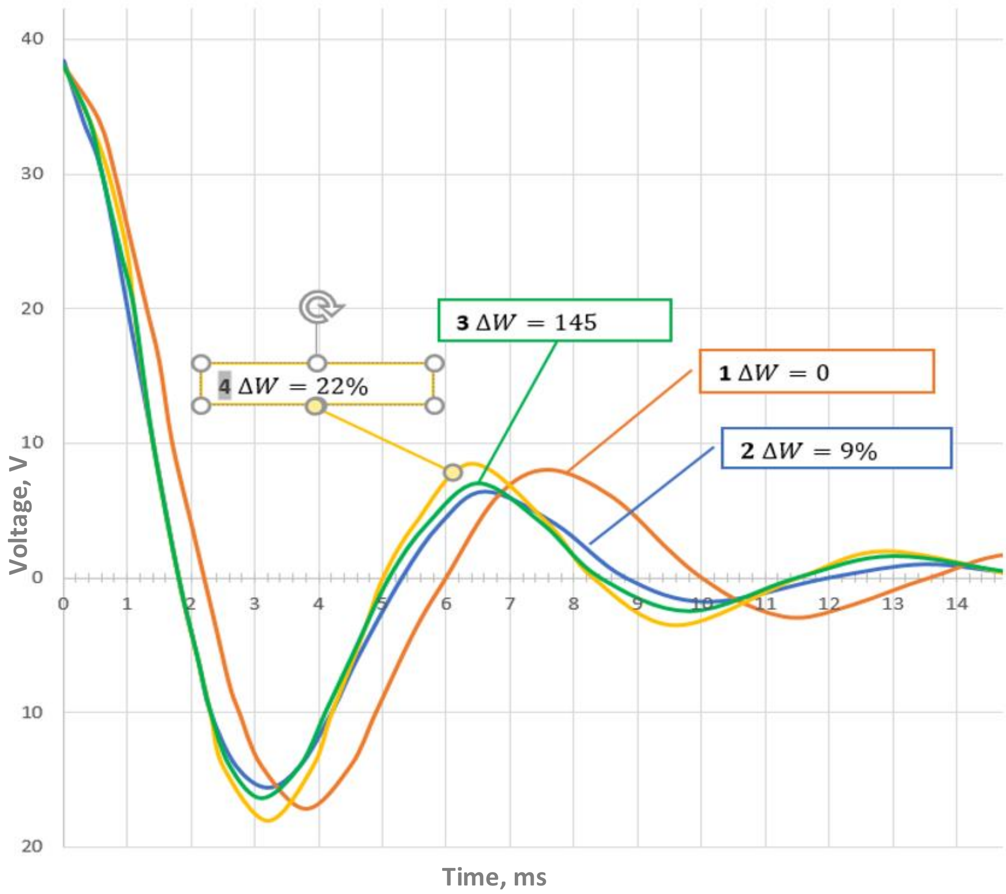


Fig. 11 – Graphs of voltage changes at the capacitor terminals when the ΔW windings are turned off, the connection diagram of the windings «star with neutral point»: curve 1 corresponds to the oscillogram of Fig. 10a, C_1 connected to terminals (u_1-w_1) of phase winding without damage; curve 2: C_3 connected to the terminals (u_1-w_1), j_2-j_3 – closed, which corresponds to 9% of the winding turns being out of order; curve 3: C_3 connected to the terminals (u_1-w_1), the terminals j_1-j_2 are closed, which corresponds to 14% of the winding turns being out of order; curve 4: C_3 connected to the terminals (u_1-w_1), the terminals j_1-j_3 are closed, which corresponds to 22% of the winding turns being out of order

Analysis of graphs (fig. 11) proves that reducing the number of turns in the winding changes both the amplitude and the time of the period of the transient process.

The time value of the period of transient processes is different and the inequality is fulfilled:

$$\Delta\tau_{baz} > \Delta\tau_{a1} > \Delta\tau_{a2} > \Delta\tau_{a3}, \quad (14)$$

where $\Delta\tau_{baz}$= 11.6 ms – the winding of the electric motor is working,
$\Delta\tau_{a1}$= 8.7 ms – closed ΔW 9%;
$\Delta\tau_{a2}$=8.1 ms – closed ΔW 14%;
$\Delta\tau_{a3}$=7.4 ms – closed ΔW 22%.

Discussion of research results. Methods of forecasting the residual resource of AM operation using both mathematical and natural thermal models are based on the expression:

$$T_{ok} = T_0 \cdot 2^{(-\theta/\Delta\theta)}. \quad (15)$$

It is assumed that T_0 – the service life of AM insulation at a constant temperature θ (°C) is 15-25 years. The spread of values T_0 in the range of (25-40)% and the influence of random factors that lead to additional thermal effects on the insulation determine the reliability of thermal forecasting methods in the range of 25-30%.

In the method of predicting the remaining service life of the AM, as the basic value of the dielectric state of the insulation of the AM windings, the constant value of the capacitor discharge time after the first disconnection of the AM from the network is taken. In the following shutdowns, the rate of reduction of the insulation properties is determined, due to any factors affecting it. The criterion that takes into account certain and uncertain factors that reduce the dielectric properties of insulation is the capacitor discharge time constant. The speed characteristics of the change of capacitor discharge time constants are given in relative units, which makes it possible to predict the residual service life of AM with an error of up to 3%, depending on the accuracy class of measuring and converting devices.

The analysis of the curve of the change in the insulation resistance of the AM windings shows that the time constant of the capacitor discharge depends on the intensity of the change in the dielectric properties of the insulation. The speed characteristic of the change in constant capacitor discharge time is a criterion parameter and allows to determine and adjust the remaining resource of AM operation in online mode.

In the method of detecting a turn short circuit in the stator windings of AM, it is advisable to use the time of the period of the transient process as a criterion parameter, which allowed to increase the reliability and sensitivity, compared to other methods, by 3-5%.

Conclusions

1. The energy that remains in the capacitor batteries after their disconnection from the power supply network allows for non-destructive test diagnostics of body and turn insulation at the time of disconnection of the AM from the power supply network.

2. A comprehensive approach to ETC energy saving due to the combination of the reactive power compensation method and the method of assessing the dynamic reduction of the dielectric properties of the insulation of the stator windings of the AM allows to reduce energy losses up to 8% and increase the reliability of the ETC due to the prevention of the residual resource of the AM.

3. The speed characteristics of the change in the constant time of capacitor discharge during local compensation of the reactive power consumed by the AM is a criterion for reducing the dielectric properties of the insulation, which allows predicting the residual resource of the AM with an error of no more than 3%.

4. The time of the transient process period when a turn short is detected is a criterion parameter that allowed to increase reliability and sensitivity by 3-5% in comparison with other methods.

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