Studies of the Change in the Time Constants of the Discharge of the Capacitor to Predict the Residual life of the Operation of the Electric Motor

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Abstract. Forecasting the resource of the electric motor makes it possible to increase the reliability of the operation of the electrical complex. The aim of the work is to study the possibility of using changes in the capacitor discharge time constants under conditions of local reactive power compensation as a criterion parameter for predicting the life of an electric motor. To achieve this goal, the following tasks were solved: an analysis of methods for predicting the resource of an electric motor was carried out, a differential equation was analyzed, and relationships between the insulation resistance and the capacitor discharge time constants were established. The most important result is the establishment of the relationship between the state of the insulation and the value of the time constant of the discharge of the capacitor. The most significant result is that the change in the time constant of the discharge is used as a criterion parameter for predicting the resource of the electric motor. The significance of the study is that the value obtained after the first shutdown of the electric motor is taken as the base value of the discharge time constant. The limiting values of the discharge time constants make it possible to estimate the resource of the electric motor after each shutdown. A method and a device for monitoring open-phase network modes are proposed, and when disconnected, control the value of the insulation resistance of the electric motor and predict the residual life of the electric motor.

Keywords: motor winding insulation, prediction, residual life, reactive power compensation, damping time constant.

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Studii ale modificării constantelor de timp ale descărcării condensatorului pentru a prezice durata de viață reziduală a funcționării motorului electric

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Abstract. Prognoza resursei motorului electric face posibilă creșterea fiabilității funcționării complexului electric. Scopul lucrării este de a studia posibilitatea utilizării modificărilor constantelor de timp de descărcare a condensatorului în condiții de compensare locală a puterii reactive ca parametru criteriu pentru prezicerea duratei de viață a unui motor electric. Pentru atingerea acestui scop, au fost rezolvate următoarele sarcini: a fost efectuată o analiză a metodelor de predicție a resursei unui motor electric, a fost analizată o ecuație diferențială și s-au stabilit relații între rezistența de izolație și constantele de timp de descărcare a condensatorului. Cel mai important rezultat este stabilirea relației dintre starea izolației și valoarea constantei de timp a descărcării condensatorului. Cel mai semnificativ rezultat este că modificarea constantei de timp a descărcării este utilizată ca parametru criteriu pentru prezicerea resursei motorului electric. Semnificația studiului este că valoarea obținută după prima oprire a motorului electric este luată ca valoare de bază a constantei de timp de descărcare. Valorile limită ale constantelor de timp de descărcare fac posibilă estimarea resursei motorului electric după fiecare oprire. Sunt propuse o metodă și un dispozitiv pentru monitorizarea modurilor de rețea în fază deschisă, iar atunci când sunt deconectate, controlează valoarea rezistenței de izolație a motorului electric și prezice durata de viață reziduală a motorului electric.

Cuvinte-cheie: izolarea înfășurării motorului, predicție, durată reziduală, compensare a puterii reactive, constantă de timp de amortizare.

Исследования изменения постоянных времени разряда конденсатора для прогнозирования остаточного ресурса эксплуатации электродвигателя

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Аннотация. Ежегодно аварийный выход из эксплуатации асинхронных электродвигателей составляет до 20–25 % от установленных, а в некоторых случаях до 30%. Прогнозирование остаточного ресурса эксплуатации электродвигателя позволяет повысить надежность эксплуатации электротехнического комплекса. Целью работы является исследование возможности использовать изменения постоянных времени разряда конденсатора в условиях локальной компенсации реактивной мощности, потребляемой электродвигателем, в качестве критериального параметра для прогнозирования остаточного ресурса эксплуатации электродвигателя. Для достижения поставленной цели были решены следующие задачи: проведен анализ тепловых, частотно-резонансных и электрических методов прогнозирования остаточного ресурса электродвигателя, проанализированы характеристические корни дифференциального уравнения второго порядка, установлены взаимосвязи изменения сопротивления изоляции обмоток и постоянных времени разряда конденсатора. Важнейшим результатом является установление однозначной взаимосвязи состояния изоляции и величины постоянной времени затухания напряжения на конденсаторе. Наиболее существенным результатом является то, что изменение постоянной временив впервые использовано в качестве критериального параметра, для прогнозирования остаточного ресурса диэлектрических свойств корпусной изоляции электродвигателя. Значимость исследования является то, что за базовое значение постоянной времени затухания принимается значение, полученное после первого отключения электродвигателя от сети. Критическое значение постоянной времени затухания процесса определяется по числовым значением фазной емкости и допустимого, не менее 0,5 МОм, сопротивления корпусной изоляции. Определены граничные значения постоянных времени затухания напряжения на конденсаторе, что позволяет сделать оценки остаточного ресурса электродвигателя по текущему состоянию изоляции электродвигателя после каждого его отключения от сети. Предложен способ и разработано устройство, позволяющее в период работы электродвигателя контролировать неполнофазные режимы напряжений сети и токовых цепей, а при отключении электродвигателя от сети контролировать величину сопротивления изоляции статорных обмоток электродвигателя и кабеля, а также прогнозируется остаточный ресурс эксплуатации электродвигателя.

Ключевые слова: изоляция обмоток электродвигателя, прогнозирование, остаточный ресурс, компенсация реактивной мощности, постоянная времени затухания.

Introduction

The simplicity and reliability of asynchronous electric motors (AM) with the use of frequency smooth speed control for the driven mechanism are the foundation of an automated electro-technological complex (ETC). According to the authors Tokarev O.V., Boryagin D.O., Sheremet O.T. [1], more than 80% of all electrical equipment in ETC consists of AM with a squirrel-cage rotor. However, the annual failure rate of AM amounts to 20-25% of the installed AM, and in some cases, it reaches up to 30%, as mentioned by the authors Gubarevich O.V., Galway S.M. [2].

The main causes of the reduction in the dielectric properties of insulation, according to the research by Gerlici J, Goolak S., Gubarevych O., Kravchenko K [3], are as follows: thermodynamic loads from starting currents, thermal overload from working currents exceeding the nominal value, local insulation overheating caused by deviations and asymmetric voltage conditions in the power supply network, contamination of stator winding sections, and high ambient temperature.

The sudden failure and breakdown of AM lead to production stoppages and significant material costs. Therefore, the assessment of the dynamic reduction in the dielectric properties of AM stator windings during the current operation of the ETC is an important task to improve the accident-free operation of the ETC and reduce material losses. The development of microprocessor devices and their integration into diagnostic and control systems of ETC contributes to the development of new methods and devices that can not only identify the cause of the pre-failure state of AM but also forecast the remaining service life of AM.

Analysis of recent research and publications.

Reducing the production cost of manufactured goods is a primary goal for any enterprise. Automation of technological complexes and reducing the number of maintenance personnel are among the directions to improve the efficiency of an enterprise. The development and implementation of non-invasive diagnostic systems, forecasting the development of emergency and pre-failure situations in electrical equipment, allow for the abandonment of planned preventive maintenance systems, reduction of personnel, and improvement of economic indicators. Many scientific works are dedicated to non-destructive testing of the technical condition of AM. For instance, Zakladny O. [4] and patents [5,6] discuss methods for monitoring the technical parameters of operating motors. An analysis of devices for detecting AM damage and means of protection is conducted. In the work of authors Mortgage O.O., Prokopenko V.V. [7], it is noted that insulation temperature is the main factor influencing the service life of the insulation. Mathematical and experimental modeling of AM thermal models allows predicting the remaining service life of insulation with an accuracy of up to 20%.

In the work of authors Metel'kov V.P., Zyuzev A.M., Chernykh I.V. [8], and in the work of Decner A., Baranski M., Jarek T., Berhausen S. [9], systems for assessing the lost resource and predicting the condition of AM winding insulation based on capacitive leakage currents are proposed. The method is based on the constant application of rectangular voltage pulses to the winding insulation and monitoring leakage currents. A decrease in the magnitude of these currents indicates a reduction in the remaining insulation life. The method is applicable for diagnostic testing and after insulation repair tests.

In the works of authors Zhao J, Brovont A.D [10], Zheng D., Lu G., Zhang P. [11], and Jensen W.R., Strangas E.G., Foster S.N. [12], methods for determining the health of insulation under the influence of impulse voltages and partial discharge monitoring are considered. It is shown that representing the asymmetric aging process is effective in detecting leakage current in the system. The method is applicable for quantitative assessment and characterization of machine insulation condition during test trials.

In the work of authors Jameson N.J., Azarian M.H., Pecht M. [13], a method for detecting insulation degradation used in low-voltage devices is presented by evaluating changes in the impedance response. It is shown that the coil impedance changes differently when subjected to various load conditions, reflecting signs of insulation deterioration due to different failure mechanisms. This method can be used to assess the insulation service life of electromagnetic coils during preventive maintenance.

In the work of authors Zanuso G., Peretti L. [14], a method for monitoring the condition of insulation is examined, based on the high-frequency ringing of stator currents that occurs after the switching of inverter converters. In this method, the response is evaluated on an additional, chaotically wound winding located on the stator of the electric motor, which serves as a prototype of an asynchronous machine. The additional winding is equipped with taps, and the change in insulation condition is induced by the installation of external capacitors. This method is used solely for insulation condition monitoring and does not allow predicting the remaining service life of the electric motor.

In the work by authors Nussbaumer P., Vogelsberger M., Wolback T. [15], a method for monitoring insulation condition changes is proposed, based on the evaluation of its high-frequency properties, which is applicable to speed-controlled asynchronous motors with solidly grounded neutral. The change in capacitance component is related to insulation degradation and is identified through frequency spectrum analysis. By applying signal processing techniques, changes in high-frequency information are extracted, and an insulation condition indicator is derived. The applicability of the method is limited and cannot be used for electric drives without speed control of asynchronous motors.

In the work by authors Bento F., Adouni A., Muxiri A.C., Fonseca D.S., Marques Cardoso A.J. [16], the diagnosis of interturn insulation of asynchronous motors is examined using two alternative thermal models of the same motor, employing lumped-parameter thermal networks and finite element methods.

The work by authors Asfani D.A., Negara I.M. [17], is dedicated to the diagnosis of interturn insulation of windings using thermal models. Testing is performed on a non-operating asynchronous motor, and changes in interturn insulation are determined. The above-mentioned scientific papers demonstrate the importance of research on reducing the dielectric properties of asynchronous motor (AM) windings' insulation and detecting critical wear. These works emphasize that the electrical insulation testing method is versatile and comprehensive. However, it should be noted that there are relatively few studies dedicated to predicting the residual lifespan of the dielectric properties of insulation. The development of non-invasive and non-destructive methods for predicting the residual lifespan of AM operation and the devices for their implementation in electrical-technological complexes (ETC) is an important factor in reducing accidents.

Objective of the study: To investigate changes in the time constants of capacitor discharge during local reactive power compensation. To develop a method and device for predicting the remaining service life of electric motors, using the rate of change of the time constants of capacitor discharge as a criterion.

Research method and materials: An electrical method was used to measure the leakage currents through the housing insulation of the stator windings of the electric motor. The type and technical characteristics of the electric motor are as follows: MS 802-4, Pn = 0.75 kW; η = 73%; cos φ = 0.76; nob = 1380 rpm. A DC power supply with voltage regulation from 50 V to 400 V was used. The oscilloscope used was OWON XDS3104E. Figure 1 shows the laboratory setup for studying the leakage currents of the stator winding's housing insulation in the AM.

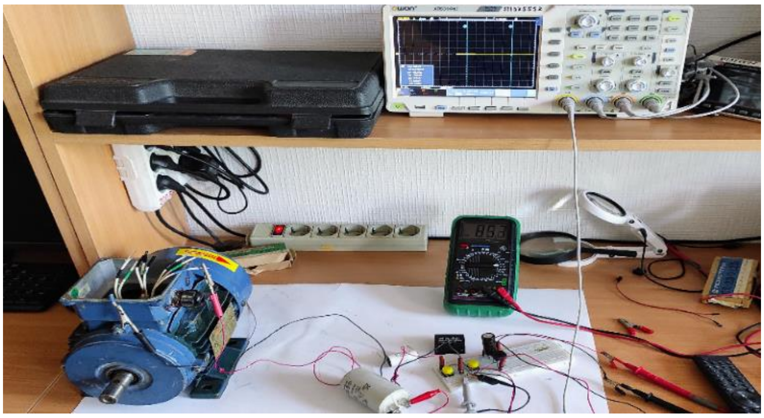


Figure 1. Laboratory setup for studying the leakage currents of the housing insulation of AM stator windings.

In the process of AM operation, the insulation of its stator windings undergoes degradation of its thermal, mechanical, and overall dielectric properties due to various factors. The residual operational lifespan of AM insulation-T_{ok}—is a target multiparametric function, comprising specific and randomly affecting factors on the winding insulation. The generalized mathematical model of the residual operational lifespan of AM winding insulation can be represented as a target function:

$$T_{ok} = f(M_{teh} \cup M_{pauz}) \qquad (1)$$

where

$$M_{teh} = \left\{\theta_1 {}^{\circ}C \cup \theta_U {}^{\circ}C \cup \theta_{kns} {}^{\circ}C \cup \theta_{dust} {}^{\circ}C \cup M_h {}^{\circ}C \cup B_i {}^{\circ}C\right\}$$

— There is a set of factors influencing the insulation of AM windings during the technological period when AM is connected to the power grid.

$\theta_1 {}^{\circ}C$—Thermal factor related to the load current exceeding the nominal value, affecting the insulation.

$\theta_U {}^{\circ}C$—Thermal factor related to voltage deviations from the nominal value, affecting the insulation.

$\theta_{kns} {}^{\circ}C$—Thermal factor related to voltage deviations and asymmetry in the power grid, affecting the insulation.

$\theta_{dust} {}^{\circ}C$—Thermal factor related to local heating of the insulation due to dust accumulation on the surface of AM stator windings.

$M_h {}^{\circ}C$—Thermal factor affecting the insulation and associated with mechanical faults in AM and the driven mechanism.

$B_i {}^{\circ}C$—Random external factors associated with the driven equipment.

$M_{pauz} = \{W_v \cup K_{acid} \cup D_i\}$ —Set of factors affecting the AM insulation during the technological pause.

W_v —Environmental humidity.

K_{acid} —Environmental acidity, a parameter typical for agricultural complexes.

K_{acid} —Random external factors.

Many factors leading to irreversible degradation of dielectric properties of insulation are random in nature. Due to this, traditional diagnostic methods and devices are directed towards one or a few influencing factors. For instance, in the methods of predicting the residual service life of insulation, considering temperature parameters, as proposed by Woldek A.I in [18], the Montzinger rule is used:

$$T_{ok} = T_0 2^{(-\theta/\Delta\theta)} \qquad (2)$$

where T_0 —is the service life of the motor insulation of a certain class at a constant temperature, years;

$\Delta\theta$ —is the constant temperature increase value.

With an accuracy of up to 20%, according to [19,20], considering temperature, vibration, start-up, and other factors, the expression (2) takes the form:

$$T_{ok} = T_0 2^{\frac{\Delta\theta_P + \Delta\theta_{HC} + \Delta\theta_{\Delta U} + \Delta\theta_{OC}}{\Delta\theta}} + T_L^{\frac{L}{L_O}} + T_S^{\frac{P}{P_O}} + \ldots T_i \quad (3)$$

where $\Delta\theta_p$ —is the insulation temperature increase of the AM windings caused by load currents during changes in the technological regime;

$\Delta\theta_{HC}$ and $\Delta\theta_{\Delta U}$ —are the insulation temperature increase of the AM windings caused by voltage deviations and asymmetry in the power supply;

$\Delta\theta_{OC}$ —is the additional temperature increase of the AM windings' insulation caused by temperature exceeding during insulation surface dusting.

T_L —is the service life of insulation associated with vibration,

L and L_O —are vibration-induced aging of insulation,

T_S —is the service life of insulation associated with AM start-ups,

P and P_O —are the thermo-mechanical aging of AM insulation caused by start-up loads,

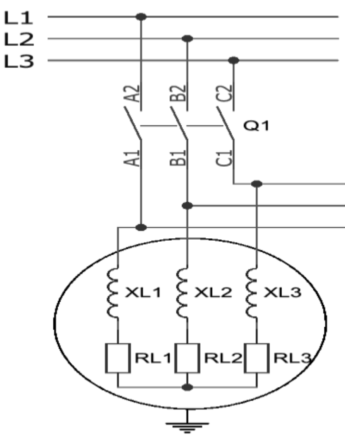
T_i —is the service life of insulation associated with the action of uncertain factors.

From the above, it follows that monitoring leakage currents through the insulation of AM windings is currently the most reliable and regulated method. According to [21], the electrical resistance of AM stator windings' insulation at voltages up to 1kV should be $R \geq 0.5$ MOhm at a temperature of $+10\ldots+30^{\circ}C$.

A promising direction in non-destructive diagnostic systems is the acquisition of informational parameters without the involvement of external power sources, as presented in works [14,15].

One of the authors of the article has developed a method for predicting the residual resource of the dielectric property of motor windings during local reactive power compensation [22]. As known from Zhezhelenko I.'s work [23], local compensation contributes to increased reliability and reduced active losses in the power supply networks of the enterprise. Figure 2 shows the single-line electrical diagram of a drive fragment with local reactive power compensation. The methodology for selecting the phase capacitance values depends on the operating mode of the AM in the technological cycle of the electrical and technological complex (ETC), as presented in Zhezhelenko I.'s work [23].

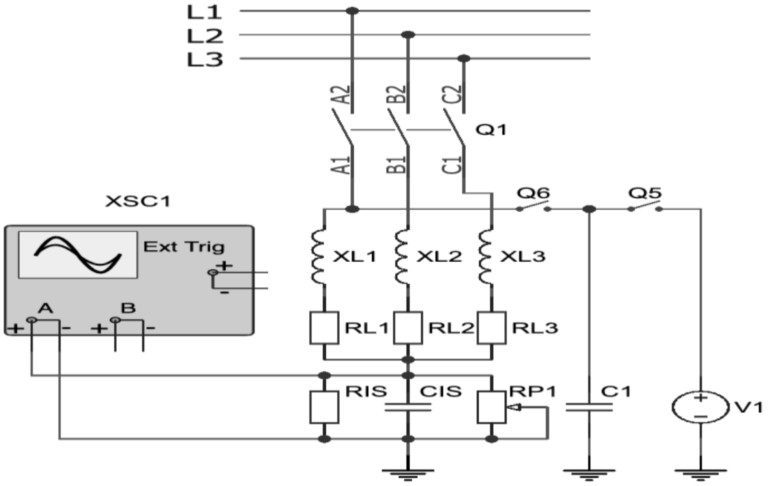
The novelty of the method for monitoring the current state of insulation based on speed characteristics of its resistance changes in the conditions of local compensation, developed by one of the authors [24], lies in the use of energy stored in capacitors as an independent source. The equivalent electrical circuit for simulating transient processes of capacitor discharge in the circuit "complex resistance of AM windings + capacitive resistance of the capacitor for reactive power compensation + complex insulation resistance" is presented in Figure 3.



C_1, C_2 C_3—phase capacitances; Q_1—three-pole contactor for AM connection to the network; Q_2, Q_3, Q_4—single-pole contactors for controlling capacitor switching; C_1, C_2, C_3, XL_1, XL_2, XL_3—inductive resistances of the stator winding phases of the electric motor; RL_1, RL_2, RL_3—active resistances of the stator winding phases of the electric motor.

Figure 2. Single-line electrical diagram of the drive in the electrical and technological complex with local reactive power compensation.

The method for monitoring the current state of the insulation of AM stator windings based on the speed characteristics of its resistance changes, under conditions of local compensation according to [22], involves the following steps: first, capacitors are disconnected from the network; second, the AM is disconnected from the network; third, after the AM comes to a complete stop, the phase capacitance is connected to the terminals "phase + AM casing." The novelty of the method lies in the ability to use the energy stored in the capacitor as an independent power source. The electrical schematic diagram of the laboratory setup, presented in Figure 3, allows building a mathematical model and simulating transient processes of capacitor discharge in the circuit "complex resistance of the AM winding + capacitor capacitance + complex resistance of the insulation" using the "Matlab" system.



RIS, CIS—represent the active and capacitive components of the substitute model for the casing insulation of AM; $RP1$—is the variable resistance that allows modeling changes in the dielectric properties of the insulation; $XSC1$—represents the oscilloscope, and $V1$—is the direct current power source.

Figure 3 shows the schematic electrical diagram used for modeling and investigating transient processes.

The equation for the circuit "complex resistance of AM winding + capacitive resistance of the capacitor + complex resistance of the insulation," denoted as $Z_{is}=\sqrt{RIC^2+CIS^2}$, is formulated according to Kirchhoff's second rule and is given by:

$$\frac{d^2 1}{dt^2}+\frac{R_{is}dt}{L_1 dt}+\frac{1}{L_1 C_1}=0 \tag{4}$$

The nature of the transient process occurring in the circuit depends on the relationship between parameters $C1$, R_{is}, and $L1$, as stated in [24]. Specifically, if the condition $\frac{1}{L_1C_1}<\left(\frac{R_{is}}{2L_1}\right)^2$ is always fulfilled, the transient process in the circuit becomes overdamped.

The variation of voltage across the casing insulation of AM is described by the expression:

$$U_{Z_{is}}=U_{C_1}(1-e^{-t/\tau_{Rr}}) \tag{5}$$

where τ_{Rr}—is the time constant of the overdamped discharge $\tau_{Rr}=C1R_{is}$ process and depends on the magnitude of the active component of the complex resistance of the insulation.

U_{C1}—represents the voltage at the terminals of the phase capacitor.

The conducted simulations demonstrated that the inequality:

$$\tau_a>\tau_b>\tau_c\leftrightarrow R_a>R_b>R_c \tag{6}$$

where τ_a, τ_b, τ_c and R_a, R_b, R_c—are the time constants and active components of the resistances of the insulation corresponding to the different modeled processes at $R_a=50.0$ MOhm, $R_a=15.0$ MOhm, and $R_a=5.0$ MOhm.

The inequality (6) allows considering the time constants of the capacitor discharge as a critical parameter for assessing the state of the dielectric properties of the insulation.

The intensity of the reduction in dielectric properties of the insulation is characterized by the parameter "rate of change of time constants" of capacitor discharges during the operation of the motor, which is determined by the expression:

$$V_{disci}=\frac{\tau_{first}-\tau_i}{\sum_i^n \Delta t_i} \tag{7}$$

where τ_{first}—is the initial time constant of the capacitor discharge at the first disconnection of the motor from the power supply,

τ_i—is the time constant of the capacitor discharge during the current disconnections of the motor from the power supply,

Δt_i—is the operating time of the motor in the current period,

n—is the number of periods of motor operation.

Mathematical modeling of the capacitor discharge processes for different resistance values of the motor's insulation allowed the development of a method for predicting the residual lifespan of the dielectric properties of the motor's insulation. The method consists of the following steps:

Firstly, the capacitor banks are disconnected from the power supply. Secondly, the motor is disconnected from the power supply. Thirdly, the highest voltage on one of the phase capacitors in the capacitor bank is determined, and the motor is connected to the terminals "phase + body" of the motor. The initial discharge time of the phase capacitor t_{disc1} is recorded, and the initial time constant of the capacitor discharge τ_{disc1} is determined. The critical value of the time constant of the phase capacitor is calculated as:

$$\tau_{crit}=C_1R_{1S} \tag{8}$$

where C_1—is the capacitance of the phase capacitor, and $R_{1S}=0.5$ MOhm is the critical value of the stator winding insulation resistance. The initial time constant of the capacitor discharge during the first disconnection of the motor from the power supply is calculated as:

$$\tau_{first}=\frac{t_{disc1}}{5} \tag{9}$$

The moments of motor start-up and shutdown in the second period of its operation are recorded, and the operating time is determined using the following expression:

$$\Delta t_2=t_{enabl2}-t_{disabl2} \tag{10}$$

where t_{enabl2} and $t_{disabl2}$—are the times of AM start-up and shutdown in the second period of its operation.

The discharge time constant of the capacitor in its second connection to the terminals "phase + body" of the motor is determined by the expression:

$$\tau_{disc2} = \frac{t_{disc2}}{5} \tag{11}$$

where t_{disc2}—is the discharge time of the phase capacitor after the second disconnection of the AM from the power supply and connection of the capacitor to the terminals "phase + body" of the motor. The rate of change of the discharge time constant of the capacitor during the second period of motor operation is calculated as:

$$V_{disc2} = \frac{\tau_{first} - t_{disc2}}{\Delta t_2} \tag{12}$$

The residual time of reduction in the resistance of the motor winding's body insulation to the critical value is determined by the expression:

$$T_{disct} = \frac{t_{disc2} - t_{crit}}{V_{disc2}} \tag{13}$$

During subsequent connections and disconnections of the AM to the power supply, the motor's operating time is recorded for each period of its operation as:

$$\Delta t_i = t_{enabli} - t_{disabli} \tag{14}$$

The discharge time constant of the capacitor in the current period is calculated using the expression:

$$\tau_{disci} = \frac{t_{disci}}{5} \tag{15}$$

The rates of change of the discharge time constants of the capacitor in the current periods of AM operation are calculated using the expression (7).

The residual time of reduction in the resistance of the motor winding's body insulation after each disconnection from the power supply to the critical value is corrected by the expression:

$$T_{disct} = \frac{t_{disci} - t_{crit}}{V_{disci}} \tag{16}$$

The residual service life of the motor is determined as a percentage using the expression:

$$Rr_{disct} = \left(1 - \frac{\tau_{first} - \tau_{crist}}{\tau_{first} - \tau_i}\right) 100\% \tag{17}$$

Method Validation

Figure 1 shows the laboratory setup for validating the developed method for predicting the residual service life of the dielectric properties of insulation, while Figure 3 presents the schematic diagram. For method validation, the capacitor capacitance $C_1 = 3\mu F$ (full reactive power compensation, according to the methodology [23]) is achieved at $C_1 = 27\mu F$.

During the first disconnection of the motor from the power supply, we determine t_{disc1}—the initial discharge time of the capacitor, τ_{first}—the initial discharge time constant of the capacitor at the initial dielectric properties of the AM stator winding insulation, τ_{crist}—the critical value of the discharge time constant of the capacitor when the insulation resistance is $R_{1S} = 0,5$ MOhm.

In the first disconnection of the motor from the power supply, the resistance $RP1$ is disconnected. By pressing the "Start" button Q_5, we connect the capacitor (e.g., capacitance C_1) to the power supply unit $V1$ with a voltage of 150 V. This way, we simulate the charging of the capacitor C_1 and consider it charged to the maximum voltage. Using the "Start" button Q_6, the charged capacitor is connected to the terminals "phase + body" of the motor. Figure 4 shows the graph of voltage changes during the discharge of the capacitor C_1.

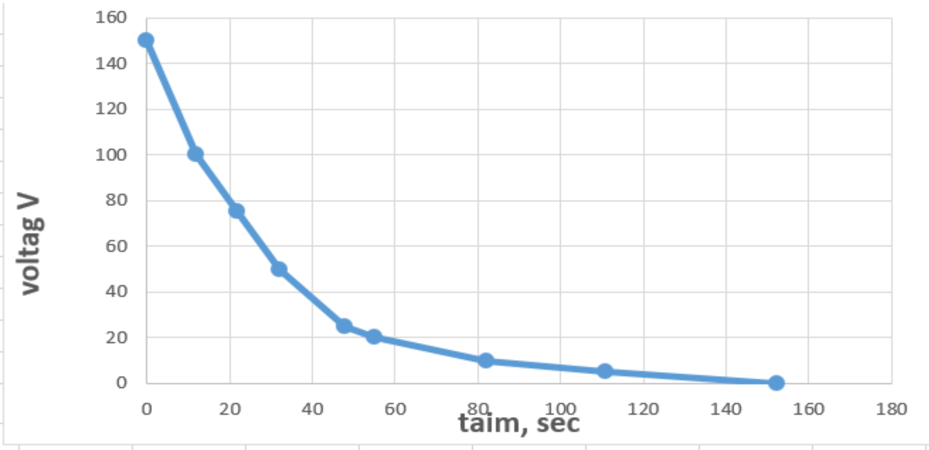


Figure 4. Voltage change graph during the discharge of capacitor C_1.

$t_{disc1} = 152,4$ seconds.

$\tau_{first} = 152,4 \big/ 5 = 30,5$ seconds.

The initial resistance of the stator winding insulation in AM, without considering the voltage measurement divider coefficient in the circuit, is:

$$R1S_{first} = \frac{\tau_{first}}{C_1} = 10,2 \text{ MOhm.}$$

We calculate τ_{crit}, the critical value of the capacitor discharge time $\tau_{crit} = 1,5$ s.

Second disconnection of AM from the power supply. The resistance is $RP2 = 20$ MOhm. Assuming that during the operation of AM, the insulation resistance decreased and is now

$$R1S_2 = \frac{R1S_{first} RP2}{R1S_{first} + RP2} = 6,6 \text{ MOhm.}$$

Therefore, the dielectric properties of the insulation have decreased by 36%. Let's assume the operating time of the electric motor was $\Delta t_2 = 10$ hours. Figure 5 shows the voltage change graph during the discharge of the capacitor.

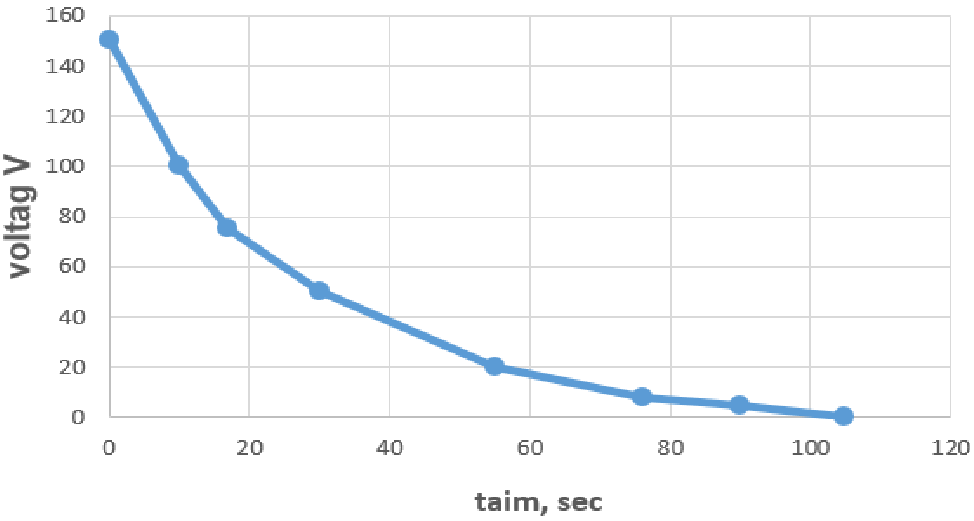


Figure 5. Voltage change graph during the discharge of capacitor C_1.

$t_{disc2} = 104,8$ seconds,

$\tau_{disc2} = 20,9$ seconds.

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

The predicted remaining operating time of AM is:

$$T_{disct}=\frac{20,9-1,5}{0,27\cdot10^{-3}}=71,9\cdot10^{-3}=19,97 \text{ hours.}$$

Thus, if the degradation, i.e., the deterioration of insulation properties, occurs at this rate, AM will operate for an additional 19.97 hours.

The residual service life of the electric motor as a percentage is:

$$Rr_{disct}=\left(1-\frac{30,5-20,9}{30,5-1,5}\right)100\%=77\%.$$

Third disconnection of AM from the power supply. The resistance is $RP3=5$ MOhm. Assuming that during the operation of AM, the insulation resistance decreased and is now

$$R1S_3=\frac{R1S_{first}RP3}{R1S_{first}+RP3}=6,6 \text{ MOhm.}$$

Therefore, the level of dielectric properties of the insulation has decreased by 70%. Let's assume the operating time of the AM was $\Delta t_3=30$ hours. Figure 7 shows the voltage change graph during the discharge of the capacitor C_1.

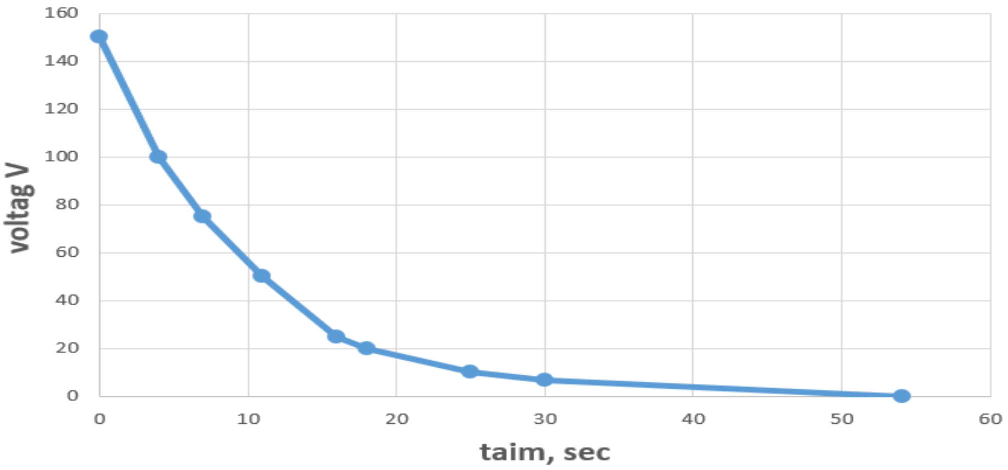


Figure 6. Voltage change graph during the discharge of capacitor C_1.

$t_{disc3}=54{,}1$ seconds, $\tau_{disc3}=10{,}82$ seconds. The rate of change of the capacitor discharge time after the third period of AM operation is:

$$V_{disc3}=\frac{20,9-10,82}{(10+30)\cdot60\cdot60}=7,5\cdot10^{-5}$$

We adjust the remaining operating time of AM, which is:

$$T_{disct}=\frac{10,82-1,5}{7,5\cdot10^{-5}}=1,242\cdot10^{5}=34,5$$

hours.

Thus, if the deterioration of insulation properties occurs at this rate, AM will operate for an additional 34.5 hours.

The residual service life of the electric motor as a percentage is:

$$Rr_{disct}=\left(1-\frac{30,5-10,82}{30,5-1,5}\right)100\%=33\%$$

Fourth disconnection of AM from the power supply. The resistance is $RP4=0,3$ MOhm. Assuming that during the operation of AM, the insulation resistance decreased and is now:

$$R1S_3=\frac{R1S_{first}RP3}{R1S_{first}+RP3}=0,292 \text{ MOhm.}$$

Therefore, the level of dielectric properties of the insulation has decreased by 100%, and further operation of AM will result in a breakdown. Let's assume the operating time of the electric motor was $\Delta_{t3}=80$ hours. Figure 8 shows the voltage change graph during the discharge of the capacitor C_1.

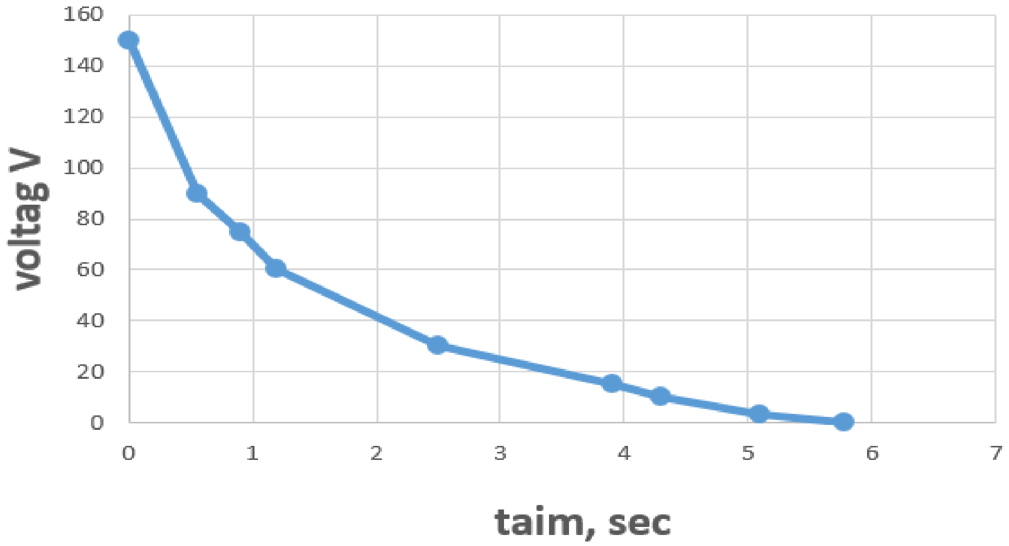


Figure 7. Voltage change graph during the discharge of capacitor C_1 .

$t_{disc3} = 5,7$ seconds, $\tau_{disc3} = 1,14$ seconds. The rate of change of the capacitor discharge time after the fourth period of AM operation is:

$$V_{disc3} = \frac{20,9-1,14}{(10+30+80)\cdot 60\cdot 60} = 4,07\cdot 10^{-6}$$

We adjust the remaining operating time of AM, which is:

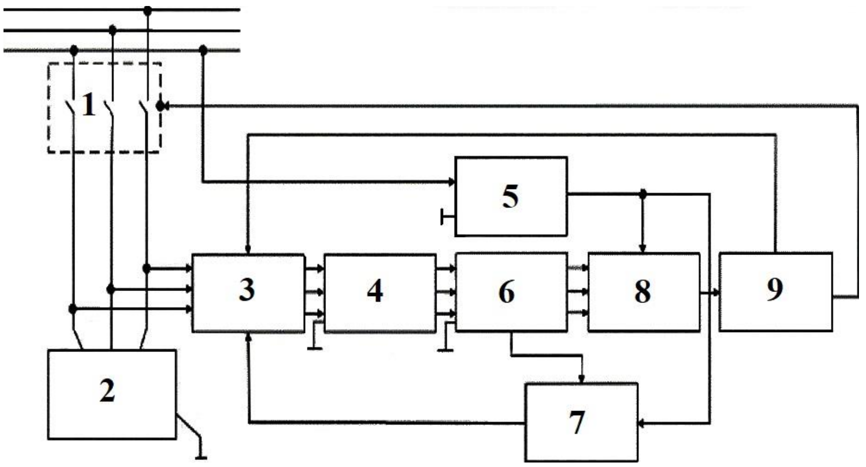
$$T_{disct} = \frac{10,82-1,5}{7,5\cdot 10^{-5}} = 2,3\cdot 10^{6} = 0,0083\text{ hours} \quad .$$

≈ 0 .

Thus, with an accuracy of up to 1%, it can be stated that the dielectric properties of the stator winding insulation of AM are depleted, and AM requires repair. The residual service life of the electric motor as a percentage is:

$$Rr_{disct} = \left(1-\frac{30,5-1,14}{30,5-1,14}\right)100\% = 0\%$$

The implementation of the developed method is carried out in the insulation monitoring and protection device for AM [25]. Figure 8 shows its block diagram.



1 - Switching device, 2 - Electric motor, 3 - Capacitor switching block, 4 - Capacitor block, 5 - Power supply block, 6 - High-impedance dividers block, 7 - Maximum positive voltage detection block, 8 - Microprocessor, 9 - Control block.

Figure 8. Block diagram of the insulation monitoring and protection device for AM.

The device allows compensating the reactive power consumed by the AM during its operation, monitoring unbalanced phases in the network, detecting current circuit interruptions, and implementing the developed method for predicting the residual lifespan of the AM's insulation dielectric properties. Furthermore, it can prevent the development of emergency situations during AM disconnections.

Discussion of Results

Methods for predicting the residual lifespan of AM operation using thermal models, both mathematical and empirical, according to [7, 15, 18, and other sources], are based on expression (2). It is assumed that T_(0·), the lifespan of AM insulation at a constant temperature θ (°C), ranges from 15 to 25 years. The scatter of T_(0·) values within (25-40)% and the influence of random factors leading to additional thermal impacts on the insulation determine the reliability of thermal prediction methods within 25-30%.

In the developed method, the time constant of the capacitor discharge after the first disconnection of the AM from the network is taken as the baseline value for the dielectric state of the AM's windings. In subsequent disconnections, the rate of insulation property degradation is determined under various influencing factors. The time constant of the capacitor discharge serves as a criterion that considers both defined and undefined factors affecting the reduction of insulation dielectric properties. The speed characteristics of the time constants of the capacitor discharges are presented in relative units, enabling the prediction of the residual lifespan of AM operation with an accuracy of up to 3%, depending on the accuracy class of measuring and converting devices.

Figure 10 illustrates the graph of resistance change of the casing insulation depending on the AM's operating time.

The analysis of the resistance change curve of AM windings' insulation shows that the time constant of the capacitor discharge is different on each linearized segment and depends on the intensity of the insulation's dielectric property changes. The speed characteristic of the time constant of the capacitor discharge allows for determining and adjusting the residual lifespan of AM operation in real-time mode.

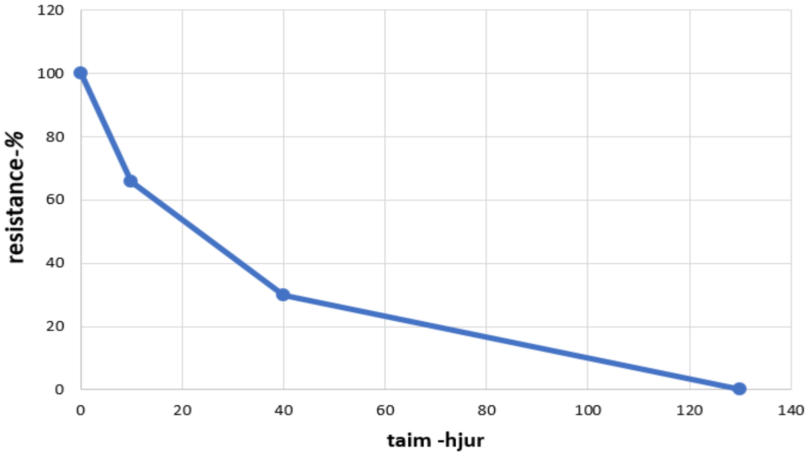


Figure 9. Graph of changes in the resistance of the casing insulation depending on the operating time of the AM.

Conclusions

The characteristics of the capacitance discharge time variation during local reactive power compensation consumed by the AM is a critical parameter for reducing the dielectric properties of insulation, allowing the prediction of the remaining AM resource with an accuracy of no more than 3%.

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