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DIELECTRIC SPECTROSCOPY OF CASING THERMOSETTING COMPOSITE ELECTRICAL INSULATION SYSTEM OF INDUCTION TRACTION ELECTRIC MACHINES

Introduction. ***Thermosetting composite electric insulation of traction electric motors undergoes significant heating, moisture, overvoltage, vibration. Purpose. The substantiation of the possibility of using dielectric spectroscopy for monitoring the state of the hull thermosetting composite electric insulating system of induction traction motors (ITM) at the technological stage of manufacturing.. Methodology. In the induction traction motors in which the phases of the stator winding are connected to a «star» and do not have a zero point output, in the case of a two-electrode connection of one of the phases and the housing, the combined characteristics of the capacitance and the dielectric loss tangent of the three-phase hull insulation system are measured. Practical value. It is established that at the second resonant frequency near 10 kHz, the tangent of the dielectric loss is the most sensitive to the state of the composite ITM insulation. Dielectric spectroscopy at alternating voltage of the combined dielectric characteristics makes it possible to evaluate the state of the hull thermosetting electrical insulating system at the final stage of manufacturing of induction traction motors.*** References 9, tables 1, figures 4.

Key words: **thermosetting composite insulation, induction traction motor, dielectric spectroscopy, replacement circuit, electrical capacitance, dielectric loss tangent, resonance frequency.**

Представлено схему замещения обмоток статора при соединении «звездой» асинхронного тягового двигателя. На основании результатов моделирования частотных зависимостей емкости и тангенса угла диэлектрических потерь установлено наличие двух резонансных частот в диапазоне 1 и 10 кГц. Показано, что измерения тангенса угла диэлектрических потерь изоляционной системы на частоте 10 кГц чувствительны к уровню диэлектрических потерь в корпусной термореактивной электрической изоляции. Результаты математического моделирования согласуются с измерениями совокупных диэлектрических характеристик корпусной композитной электроизоляционной системы трех фаз. Библ. 9, табл. 1, рис. 4.

Ключевые слова: **термореактивная композитная изоляция, асинхронный тяговый двигатель, диэлектрическая спектроскопия, схема замещения, электрическая емкость, тангенс угла диэлектрических потерь, резонансная частота.**

Introduction. Difficult operating conditions for DC and AC traction high-voltage machines present increased requirements for electrical insulation. Thus, thermosetting composite electric insulation of traction electric motors (TEM) undergoes significant heating, moisture, overvoltage, vibration. The insulation must have sufficient electrical and mechanical strength, be heated and moisture resistant. Modern electrical insulating materials and technologies for their manufacture have made it possible to improve the systems of high-voltage thermosetting composite electric insulation of motors, improve their operational and energy characteristics [1]. The use of insulation of the heat resistance class H (180 °C) improves the reliability of the TEM, allows for the same size to realize a greater power. Such isolation systems are capable of operating at least 50,000 hours at temperature of 180 °C and withstanding overvoltages above 10 kV.

For electric insulation with a high content of mica and epoxy resin, the TEM winding is used both as a vacuum-injection impregnation technology and pre-impregnated tapes. The vacuum-injection impregnation procedure guarantees high mechanical strength, especially the frontal part of the winding and high electrical strength. During the process of impregnating the insulation system, the viscosity of the resin is measured; temperature of impregnation and curing; holding time under pressure; reduced and excess pressure.

Problem definition. At all stages of manufacturing TEM: before impregnating the armature and coils, after heat treatment (baking) of the armature and coils, in the finished motor – the insulation resistance and electrical strength are checked [2, 3]. Insulation of rods (coils) of machines with power of more than 5 MW and voltage greater than 6 kV for the control of manufacturing technology is subjected to an additional test [4]: measurement of the dielectric loss tangent tgδ of insulation, depending on the applied test voltage at normal air temperature. Measurement of the tangent of the dielectric loss angle of insulation is performed by the Schering bridge at frequency of 50 Hz. Such tests allow us to indirectly judge the presence of air inclusions caused by the stratification of thermosetting insulation as a result of its incomplete polymerization. Measurements at only one frequency of 50 Hz do not allow to fully reveal the residual moisture and stratification of the thermosetting composite insulation system of TEM. High operational reliability of traction electric motors is determined by the quality of insulation of windings, which must have a high moisture resistance.

In the last decade, **dielectric spectroscopy** has gained considerable theoretical and experimental development. In dielectric spectroscopy, an analysis is made of the function of the complex permeability ε^* of insulation by the frequency and voltage range [5-7]:

$$\varepsilon^* = \varepsilon' - i\varepsilon'' = \varepsilon - i\sigma / \omega\varepsilon_0 ,$$

where ε' is the real part of the complex dielectric permeability (relative permeability ε) which determines the electrical capacity of the insulation; ε'' is the imaginary part that determines the energy loss in insulation: $\varepsilon'' = \sigma / \omega\varepsilon_0$; σ is the specific volume conductivity of the insulation material, S/m; ω is the circular frequency of the applied current, rad/s; $\varepsilon_0 = 8.85\cdot10^{-12}$ F/m is the electrical constant.

The tangent of the dielectric loss angle determines the losses for electrical conductivity and polarization

$$tg\delta = \frac{\varepsilon''}{\varepsilon'}.$$

The frequency dependence of the capacitance and tangent of the dielectric loss angle allows one to judge the state of the thermosetting insulation system of TEM.

The goal of the paper is substantiation of the possibility of using dielectric spectroscopy for monitoring the state of the hull thermosetting composite electric insulating system of induction traction motors at the technological stage of manufacturing.

The method of aggregate measurements of the dielectric parameters of a thermosetting insulating system. In induction traction motors (ITM) in which the phases of the stator winding are connected to a «star» and do not have a zero point output (a blind connection of the phases of the winding), to measure the capacitance and tangent of the phase loss dielectric loss, it is advisable to use two-electrode connection of two phases to the measuring circuit. This is a method of aggregate measurements without shorting the rest of the phases that are not involved in the measurements. For this, it is necessary to perform *three measurements* (indices *a*, *b*, *c* in (1)) based on the results of which, based on the solution of the system of linear algebraic equations for capacitances and the tangent of the dielectric loss angle (1), the dielectric parameters of the windings insulation of each phase (indices 1, 2, 3 in (1)) connected in a «star» [8]

$$\left.\begin{aligned} \frac{1}{C_1}+\frac{1}{C_2}&=\frac{1}{C_a}\\ \frac{1}{C_1}+\frac{1}{C_3}&=\frac{1}{C_b}\\ \frac{1}{C_2}+\frac{1}{C_3}&=\frac{1}{C_c}\end{aligned}\right\};\quad \left.\begin{aligned} tg\delta_1\frac{C_2}{C_1+C_2}+tg\delta_2\frac{C_1}{C_1+C_2}&=tg\delta_a\\ tg\delta_1\frac{C_3}{C_1+C_3}+tg\delta_3\frac{C_1}{C_1+C_3}&=tg\delta_b\\ tg\delta_2\frac{C_3}{C_2+C_3}+tg\delta_3\frac{C_2}{C_2+C_3}&=tg\delta_c\end{aligned}\right\}. \quad (1)$$

Aggregate dielectric characteristics of the hull thermosetting insulation system of ITM. In the case of a two-electrode connection of one of the phases and the housing, the combined characteristics of the capacitance C and the dielectric loss tangent tg*δ* of the three-phase hull insulation system are measured. Fig. 1 shows the circuit for replacing the stator windings of ITM [9]. The windings are connected according to the «star» circuit. Zero point *O* is not available for measurements. The diagram denotes: *R*1, *L*1, *R*2, *L*2 are the ohmic resistance and inductance of the windings of each phase; *C*3, *R*3 are the capacitance of each phase relative to the body (the capacity of the housing insulation system) and the equivalent resistance of each phase. Resistor *R*3, connected in parallel, reflects the insulation leakage resistance (when measured at a constant voltage) or the equivalent dielectric loss resistance (when measured at alternating voltage). The simplified two-element circuit of substitution of the housing insulation does not reflect the relaxation processes in the insulation associated with the accumulation of space charges.

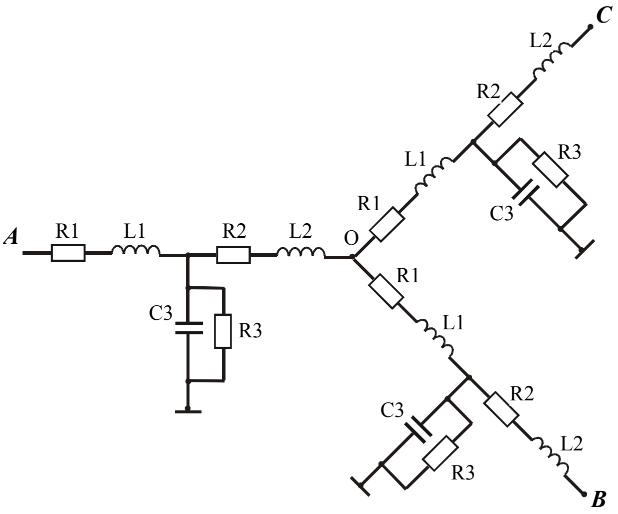

Fig. 1. Circuit of replacement of stator windings of ITM

The complex resistance of phase A is defined as

$$\underline{Z_A}=R_1+j\omega L_1+\left[\frac{R_3(-j\frac{1}{\omega C_3})}{R_3-j\frac{1}{\omega C_3}}\right] \| \left[R_2+j\omega L_2+\frac{R_1}{2}+\right. \quad (2)$$

$$\left.+\frac{j\omega L_1}{2}+\frac{\frac{R_3}{2}(-j\frac{1}{\omega 2C_3})}{\frac{R_3}{2}-j\frac{1}{\omega 2C_3}}\right],$$

where by || the parallel connection of fragments of the substitution circuit is indicated.

Assuming the same ohmic resistance and inductance of the half windings of each of the phases $R1 = R2 = R_L$, $L1 = L2 = L$, one can define the complex resistance $\underline{Z_L}$ and conductivity $\underline{Y_C}$ of the half winding

$$\underline{Z}_L=\frac{1}{2}(\frac{R_L}{2}+\frac{jw\,L}{2}),\ \underline{Z}_c=r-\frac{j}{w\cdot C},\ \underline{Y}_c=\frac{1}{\underline{Z}_c}.$$

Complex impedance Z_{LC} (complex conductivity Y_{LC}) of the second half of the winding and two halves of other two windings

$$\underline{Z}_{LC}=\underline{Z}_L+\frac{\underline{Z}_L+\underline{Z}_C}{2},\ \underline{Y}_{LC}=\frac{1}{\underline{Z}_{LC}},\underline{Z}=\underline{Z}_L+\underline{Z}_{CLC}\cdot$$

$$\underline{Y}_{CLC}=\underline{Y}_C+\underline{Y}_{LC},\ \underline{Z}_{CLC}=\frac{1}{\underline{Y}_{CLC}},\underline{Z}=\underline{Z}_L+\underline{Z}_{CLC}\cdot$$

Then the required total dielectric characteristics of the insulation system of the windings relative to the body are determined on the basis of (3)

$$R_e=\text{real}(\underline{Z}),\ Ce=-\frac{w}{\text{imag}(\underline{Z})},\ \text{tg}\delta_e=R_e\cdot C_e\cdot w. \quad (3)$$

Model frequency dependences of the combined dielectric characteristics of the hull insulation system. Fig. 2, 3 show the frequency dependences of the capacitance and tangent of the dielectric loss angle of the hull insulation system of the ITM windings, constructed on the basis of (2), (3). In the frequency range from 1 to

10 kHz, the windings have two resonant frequencies. The first one is in the 4.2 kHz region; the second one is near the frequency of 10 kHz. Measurements near 10 kHz are very sensitive to the level of dielectric losses in the insulation (Fig. 3). At measuring tgδ of actually *insulation* from 0.074 = 7.4 % to 0.012 = 1.2 % (i.e. almost 6 times – see Fig. 4, frequency 10 kHz), the result of measuring the parameter tg$\delta_{10\mathrm{kHz}}$ of the entire winding changes tens – hundreds of times (Fig. 3).

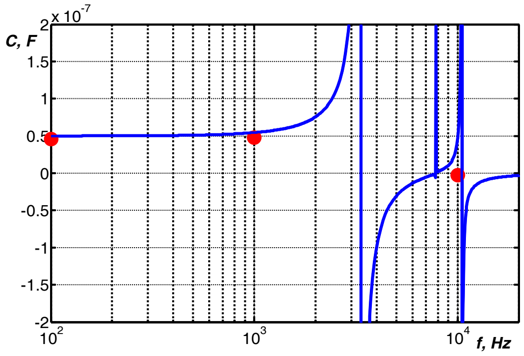

Fig. 2. Dependence on the frequency of the effective capacitance of the windings relative to the housing (capacity of the housing insulation system): points – experimental data; solid line – calculation according to the substitution circuit in Fig. 1

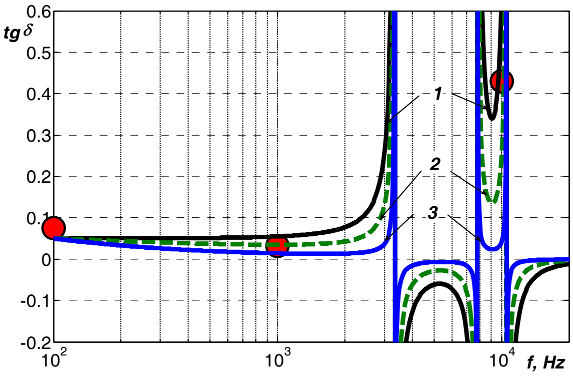

Fig. 3. Dependence on the frequency of the tangent of the dielectric loss angle of the hull insulation system:
points – experimental data;
solid lines – calculation by the substitution circuit in Fig. 1

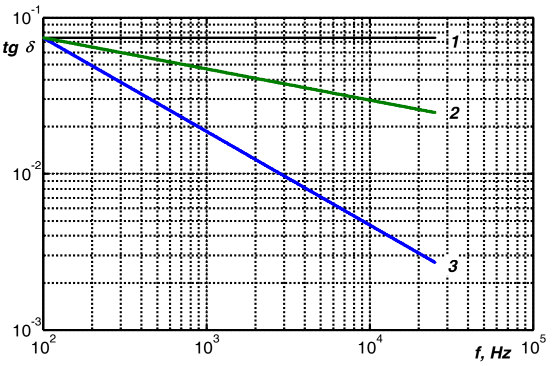

Fig. 4. Dependences on the frequency of the tangent of the dielectric loss angle of the hull thermosetting insulation adopted in calculating the frequency dependences of *C* and tgδ of the winding insulation system

In Fig. 3 curves 1-3 are constructed under the assumption: curve 1 – with a constant value of tgδ of thermosetting composite insulation; 2 and 3 – with the power law of change of the tangent of the dielectric loss angle of insulation: 2 – at tgδ = tg$\delta_0(f_0/f)^{0.2}$; 3 – at tgδ = tg$\delta_0(f_0/f)^{0.4}$, where the indices «0» correspond to the value at the frequency of 100 Hz.

Table 1 shows the results of measurements of the total dielectric characteristics of the hull insulation system of the ITM windings. The measurements are performed at three frequencies: 100 Hz, 1 kHz and 10 kHz. The first two frequencies turned out to be lower, and the third one was higher than its own resonant frequency (Table 1). Hence, the resonance frequency of the windings (the first resonance frequency) is in the range 1-10 kHz. When measuring at frequencies above resonance, the *aggregate* parameters of both the main and *parasitic* circuits are measured. Thus, when monitoring the capacitance and tangent of the dielectric loss angle tgδ of the hull insulation system at frequency of 10 kHz (above resonant), the readings of the immittance meter become negative: C = –2.8639 nF < 0. This means that the complex resistance of the «three phase-housing» insulation gap at this frequency is no longer capacitive, but inductive.

Table 1

Aggregate dielectric parameters of the induction motor hull system

Induction motor : - voltage 1.875 kV; - power 1200 kW. Insulation class H	Frequencies of measurement, kHz					
	0.1		1		10	
	C, nF	tgδ, %	*C*, nF	tgδ, %	*C*, nF	tgδ, %
	45.639	7.435	47.473	3.151	–2.8639	43.016

Conclusions. The results of modeling the frequency dependences of the aggregate dielectric characteristics on the basis of the stator winding replacement circuit for the «star» connection of an asynchronous traction motor indicate the presence of two resonant frequencies in the 1 and 10 kHz range. At frequency of 10 kHz, the tangent of the dielectric loss angle of the entire insulation system of the windings changes by a factor of tens – hundreds which makes it possible to monitor the state of the composite insulation at this frequency. The presence of residual moisture in the body insulation leads to an increase in tgδ of the body thermosetting composite system with decreasing frequency.

Dielectric spectroscopy of aggregate dielectric characteristics at alternating voltage allows to evaluate the state of the body thermosetting electrical insulating system at the final stage of manufacturing of induction traction motors.

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