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COMMUNICATIONS

DIAGNOSTICS OF GLASS–EPOXY INSULATING MATERIALS

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In the present work we introduce new diagnostic methods that were verified in laboratory conditions with glass-epoxy insulating materials. We describe the principle of these methods, test objects, the experiment itself and its evaluation, including the discussion of test results.

Keywords: diagnostics, diagnostic method, insulating system, insulating material, electrical machine.

1 INTRODUCTION

Recently, the enhanced requirements for the economy and life of electrical machines have brought about increasing demands on the output of electrical machines. This fact is associated primarily with the increased stress of an insulating system of electrical machines that becomes one of the machine parts showing the highest failure rate. Malfunctions of insulating systems are mainly caused by breakdown, which results in losing their insulating properties. As the life of any system is determined by the life of its weakest element, we focused attention on the problem of the diagnostics of insulating materials for the winding of electrical machines. Our primary objective is to find such diagnostic quantities that would reflect the condition of any insulating system monitored in a non-destructive and simple way.

If a diagnostic method has to be able to provide enough information, it has to be based on the knowledge of the physical nature of ongoing processes. The present work is concerned with the method for estimating the critical voltage of thermal breakdown, the method of the temperature dependence of internal conductivity, and the method of the activation energy of dominant polarization processes. This results in deriving diagnostic quantities in the form of factors K_C, B_v and B_a, and in analyzing them with regard to their suitability for achieving our objectives. Therefore, in the present work we describe the principle of the methods used, test objects, the experiment itself and finally its evaluation, including the comprehensive discussion of test results.

2 THEORETICAL PART

The method for estimating the critical voltage of thermal breakdown, derived from the temperature dependence of insulation resistance, is based on the analysis of the equation which describes the balance between the heat generated due to dielectric loss and the heat dissipated into the environment. This equation may be expressed in the form

$$EJ = \frac{\mathrm{d}G}{\mathrm{d}t} + W_Z\,, \tag{1}$$

where E is the intensity of an electric field, J is current density, G is the internal energy of the element of volume, t is time, and W_Z is dissipated power. It is very difficult to solve this equation exactly as both the internal energy and dissipated power are given in the form of very complex expressions. They consist of several terms that are in close relation to the internal structure of a material. A general theory, based on the above equation, may be constructed provided that these two quantities, G and W_Z, are simplified. Hlávka concerned himself with the solution of equation (1) and derived a relation for the critical voltage of thermal breakdown of a thin plane plate in the form

$$U_C = \sqrt{aR_C\big(T_C - T_0\big)}\,, \tag{2}$$

where a is cooling constant, R_C is internal resistance at critical temperature, T_C is the critical temperature of thermal breakdown, and T_0 is ambient temperature. Critical voltage represents an asymptotic value of the voltage-time characteristic. Therefore, it may be considered a quality suitable for evaluating the state of insulation. The estimate of this value, determined on the basis of measuring the temperature dependence of insulation resistance, may be used in diagnostics. As it is quite difficult to determine the value of cooling constant a (which involves several factors that can be determined exactly for some of the elementary arrangements only), in order to determine the degree of relative deterioration of an insulating material, it is sufficient to evaluate a quantity proportional to critical voltage

$$K_C = U_C/\sqrt{a} = \sqrt{R_C(T_C - T_0)}\,. \tag{3}$$

Upon the loss of functional power with composite insulating materials used for the winding insulation of rotary

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electrical machines, the mechanism of thermal breakdown may be taken into consideration in general. Enhanced electric conductivity, to a very large extent influenced by temperature at the breakdown point, is characteristic of this mechanism. Considering that conductivity is of an ionic nature with commonly used insulating materials, these ions may include oxidation products, catalyst residues, dissociable terminal groups, *etc.* Electric conductivity with composite insulating materials involves usually several kinds of ions at the same time. Thus, internal conductivity may be expresses by the general relation

$$\gamma_v = \sum n_i \, q_i \, u_i \,, \tag{4}$$

where n_i is concentration, q_i is electric charge, and u_i is the drift mobility of i-ion. Explicit expressions for concentration and mobility may be derived from the model of a double-potential well. Based on these expressions, the temperature dependence of internal conductivity for a hypothetical substance containing an ion of i-kind takes the form

$$\gamma_{vi} = \frac{A_{1i}}{T} \exp\bigl(W_{vi}/kT\bigr) \,, \tag{5}$$

where A_{1i} is a factor, T is absolute temperature, W_{vi} is the activation energy of a conductivity process (including the energy necessary for the production of a particular kind of ion and the energy required for ion motion), and k is the Boltzmann constant. In practice, relation (5) is replaced frequently by the simplified expression

$$\gamma_{vi} = A_i \exp\bigl(-B_{vi}/T\bigr) \,, \tag{6}$$

which is a straight line with a slope of $-B_{vi}$ in the graphic presentation of $\ln \gamma_{vi} = F\bigl(1/T\bigr)$. The contents of term B_{vi} is obvious upon the comparison of relations (5) and (6). Considering that the kind of distribution of activation barriers for individual mechanisms of conductivity is unknown, terms B_v and W_v have a character of effective values upon the approximate application of relation (6). Thus, term B_v can be used for diagnostic purposes. It can be derived from the temperature dependence of conductivity, for instance, by the method of least squares.

A working hypothesis for the method of the activation energy of dominant polarization processes stems from the utilization of dielectric absorption which takes place in insulating materials at various temperatures after an electric field has been connected. For this purpose, it is possible to use the relation

$$i = A \, t \exp\bigl(-t/\tau_0\bigr) \,, \tag{7}$$

where i is absorption current, A is a constant, and τ_0 is the mean relaxation time of polarization. The mean relaxation time of polarization depends upon temperature according to the relation

$$\tau_0 = \tau_{01} \exp\bigl(W_p/kT\bigr) \,, \tag{8}$$

where τ_{01} is a constant, W_p is the effective activation energy of dominant polarization processes, k is the Boltzmann constant, and T is absolute temperature. Equation (8) may be transformed into the form

$$\tau_0 = \tau_{01} \exp\bigl(B_a/T\bigr) \,, \tag{9}$$

where quantity B_a is proportional to the effective activation energy of dominant polarization processes, with a proportionality constant being $1/k$. Thus, term B_a can be used for diagnostic purposes. It can be derived from dielectric absorption proceeding at various temperatures. The procedure being outlined is just a rough simplification as the theory presumes only one mean relaxation time. The interactions of individual dipole particles fluctuate considerably with most insulation materials, and there is also a significant difference in relaxation times. In the event of an infinite number of relaxation times, these are distributed continuously by a particular distribution function around the most probable relaxation time. This issue is the subject of our interest and study at the present time, and therefore no further information has been presented.

3 EXPERIMENTAL PART

All the methods described herein were verified in laboratory conditions with the samples of glass-epoxy material, Vetronit EP G–11, sort 432.82 with a nominal thickness of 0.2 mm, during the thermooxidative ageing process. The samples were provided with a graphite-base three-electrode measuring system and subjected to the ageing process in a hot-air sterilizer at a temperature of 180 °C. In a non-ageing state and then after 4, 8, 12, 16, 24, 33, 40, 56 and 60 days, their resistance was measured by a classic volt-ampere method at a voltage of 200 V in the 23 to 120 °C temperature range. At the end of measurement, the breakdown voltage U_B was determined for each sample by gradually increasing direct-current voltage from zero until breakdown. Five samples were available for each ageing time.

4 EXPERIMENT EVALUATION AND THE DISCUSSION OF TEST RESULTS

Based on an algorithm described in [1], values R_C and T_C were derived from the values measured for each sample. The estimate of K_C, which is proportional to the critical voltage of thermal breakdown, was calculated from these values according to relation (3). For the purpose of a further procedure, the arithmetical mean of values K_C was used. During the whole experiment, we placed much emphasis on determining the statistical dependence of the critical voltage of thermal breakdown versus direct-current breakdown voltage. Therefore, correlation analysis was performed. The dependence of the relative change in values K_C and U_B (K_C/K_{C0}, U_B/U_{B0}, where K_{C0} and U_{B0} are the initial values of respective quantities)

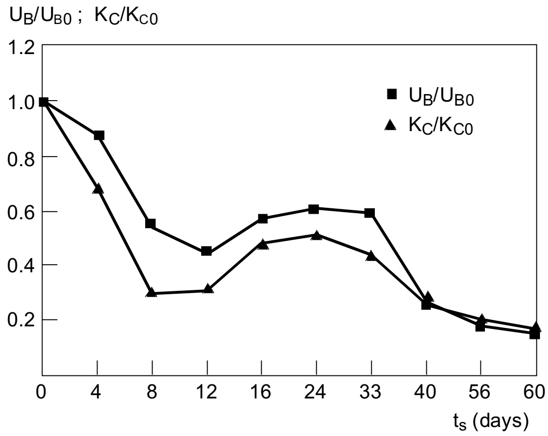

Fig. 1. Dependence of the relative changes K_C/K_{C0}, U_B/U_{B0} versus ageing time t_s.

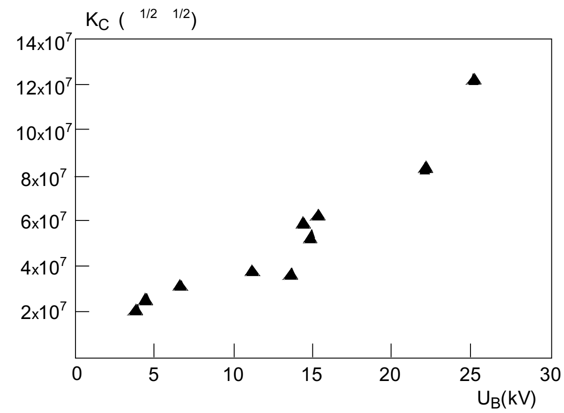

Fig. 2. The dependence of K_C versus U_B of 0.2 mm thick Vetronit EP G–11 sample.

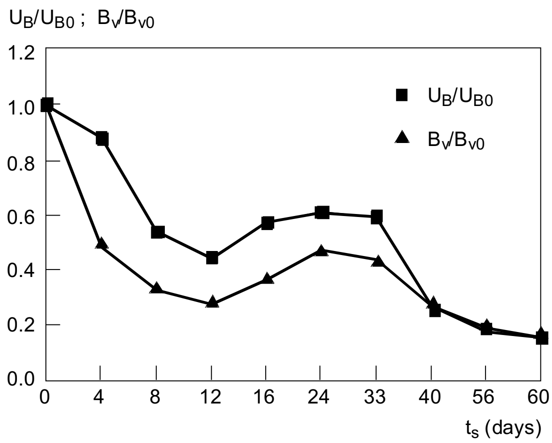

Fig. 3. Relative change in values U_B and B_V versus ageing time.

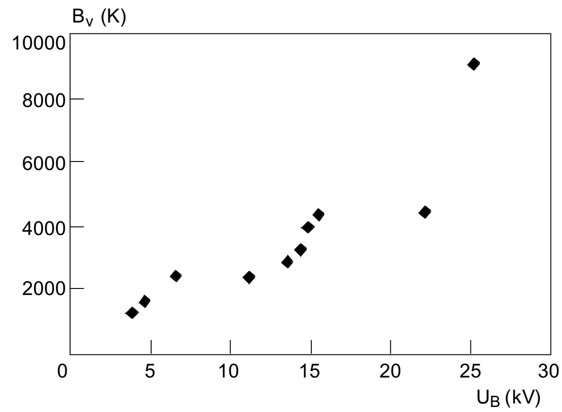

Fig. 4. Dependence of B_V on U_B of 0.2 mm thick Vetronit EP G–11 sample.

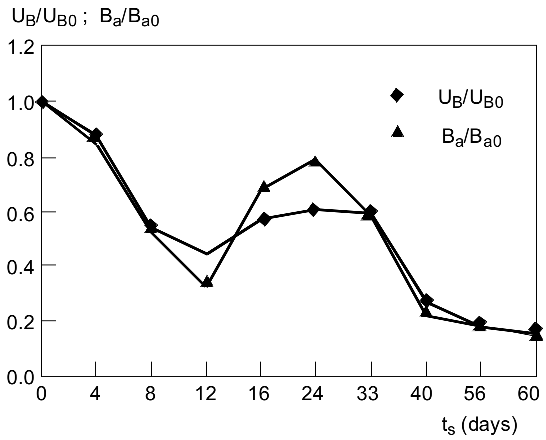

Fig. 5. Relative change of U_B and B_a versus ageing time.

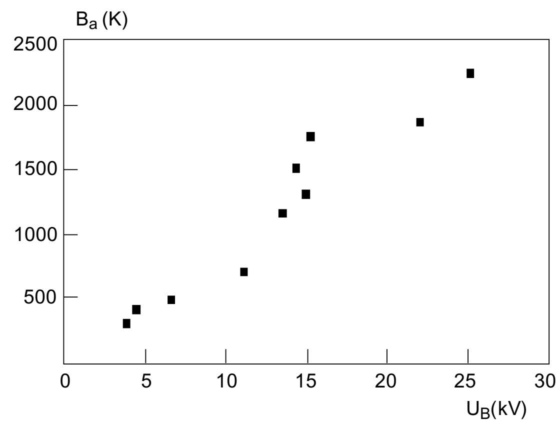

Fig. 6. Dependence of B_a on U_B of 0.2 mm thick Vetronit EP G–11 sample.

versus ageing time t_s is graphically illustrated in Fig. 1, and the dependence of K_C versus U_B is shown in Fig. 2.

Internal conductivity was calculated from the values of internal resistance that were measured in the above temperature range for individual ageing times. From the data measured, the amount of B_V was determined for each sample by the method of least squares according to relation (6). The arithmetical mean of values B_V was used for further evaluation and to determine the statistical dependence of this factor versus direct-current breakdown voltage. Similarly to the above situation, the dependence of the relative change in values B_V and U_B versus ageing time is graphically illustrated in Fig. 3, and the dependence of B_V versus U_B is shown in Fig. 4.

The mean relaxation time of polarization was determined according to equation (9). The amount of B_a was calculated by the method of least squares in the above temperature range for individual ageing times. The arithmetical mean of values B_a was used for further evaluation and to determine the statistical dependence of this factor versus direct-current breakdown voltage. Similarly to the above situations, the dependence of the relative change in values B_a and U_B versus ageing time is graphically illustrated in Fig. 5, and the dependence of B_a versus U_B is shown in Fig. 6.

It follows from the experiment evaluation that all the methods showed good consistency between the diagnostic quantities and breakdown voltage as well as the existence of linear correlation dependence between both quantities. Based on the statistical tests, it has been verified that the difference between the correlation coefficients obtained is statistically insignificant (0.94 for the dependence of K_C *vs* U_B, 0.89 for the dependence of B_V *vs* U_B, and 0.96 for the dependence of B_V *vs* U_B). Therefore, the method for estimating critical voltage, the method of the activation energy of conductivity, and the method of the activation energy of dominant polarization processes may be considered approximately equivalent. Further, it has been found out that all diagnostic quantities undergo statistically significant changes during the thermo-oxidative ageing process, with a characteristic decrease being observed for longer ageing times. The graphic illustrations in Figs. 1, 3 and 5 show several changes in the behaviour of the diagnostic quantities monitored and direct-current breakdown voltage as a function of ageing time: a decrease at an early stage, followed by a temporary increase, and finally a monotonous decrease. It may be estimated that the process of epoxy resin hardening still occurs at the initial stage of the ageing process of glass-epoxy materials as well as the failure of the binder-to-glass fibre adhesion. We assume that the failure of the binder-to-glass fibre adhesion is a crucial process at the first stage of the ageing process with regard to electric strength, which is manifested by a decrease in electric strength. These changes are conquered at a later stage as the properties of the epoxy resin itself improve, which results in a temporary increase in electric strength. Irreversible processes in the structure of materials occur at the final stage of the ageing process, accompanied by a permanent decrease in breakdown voltage. We further assume that the diagnostic quantities monitored are sensitive to the above changes, which is also demonstrated by their behaviour as a function of ageing time.

5 CONCLUSION

Three new diagnostic quantities were verified in laboratory conditions with an epoxy resin-base non-homogeneous material. It follows from the experiment evaluation that the method for estimating the critical voltage of thermal breakdown, the method of the temperature dependence of internal conductivity, and the method of the activation energy of dominant polarization processes reflect the changes in the insulating material being tested. The diagnostic quantities in the form of factors U_K, B_v and B_a, relevant to these methods, are statistically dependent on direct-current breakdown voltage and sensitive to those processes that are associated with the procedures occurring in an insulating material at an early stage of the ageing process. A characteristic decrease is observed for longer ageing times. Based on the results obtained, it may be assumed that the diagnostic methods described herein could be suitable for monitoring the state of insulation of materials used for the winding of rotary electrical machines. These methods are also undemanding with regard to instrumentation and subsequent mathematical processing. Their theoretical basis consists in measuring the temperature dependence of dielectric absorption which takes place in insulation materials at various temperatures after an electric field has been connected. Therefore, the methods may be applied during the cooling of an electrical machine, *eg* during a prophylactic inspection.

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Miloš Hammer (Doc, Ing, CSc) was born in Nové Město na Moravě, Czech Republic on June 16, 1953. Doc. Hammer graduated from Brno Technical University, Electrotechnical Faculty in the branch of electrical material technology. This discipline was focused on the physics and the technology of electrotechnical and electronic materials, electrical insulating technology of materials and the technology and construction of electrical machines and instruments. He received the research degree of "Candidate of Technical Sciences — CSc" in the same branch in 1986, and he was appointed as Senior Lecturer in the branch of electrical technology in machinery in 1989. After a four-year practice in industry, he has been working at Faculty of Machinery Engineering, Brno Technical University since 1981. When he had entered the faculty, he was involved in solving many research tasks as a project manager or a participant who solved the problem. The problems were focused on the technology, development and verification of new insulating and magnetic materials which were used for the production of electrical rotary machines. Furthermore, the topics were focused on reliability of electrical machines, mainly searching for the methods of their assessment. Doc. Hammer has studied the diagnostics of insulating systems of electrical machines since 1991. This resulted in the elaboration and verification in practical terms of many diagnostic methods that allow to specify both the conditions of insulating materials of electrical machine windings and the prognosis of their life by non-destructive methods. Recently, doc. Hammer has applied the theory of fuzzy sets for the establishment of mathematical models for technical phenomena and processes, and furthermore, he concentrated on neuron networks which can be used in technical diagnostics, system modelling and prediction of their life.