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COMPLEXITY OF DETERMINING FACTORS FOR THE THERMAL EVALUATION OF HIGH VOLTAGE INSULATION SYSTEMS ON THE EXAMPLE OF ROTATING MACHINES

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Abstract

The thermal evaluation process as well as a choice of test and end-point criteria for single insulating materials is clearly defined, whereas the situation for insulation systems is much more complex. In this paper thermal and electrical ageing models as theoretic fundamentals of accelerated ageing are summarised, followed by a discussion of the normative determining factors for the thermal evaluation of insulation systems for rotating machines.

1 Introduction

The increasing demand for higher efficiency and higher power output of rotating machines involves increasing temperatures during operation. For the thermal classification of new insulation systems, long-term thermal evaluation procedures have to be carried out.

Thermal and electrical ageing models are the theoretic fundamentals of accelerated ageing tests. These models are presented in chapter 2. The interaction between different IEC standards for the thermal evaluation of insulating materials and systems is covered in chapter 3. Chapter 4 deals with aspects of the thermal evaluation procedure for the insulation system of rotating machines.

2 Thermal and Electrical Ageing Models

The insulation life of motors and generators is affected by many different stresses such as thermal, electrical, ambient and mechanical (so called TEAM stresses, see Fig. 1).

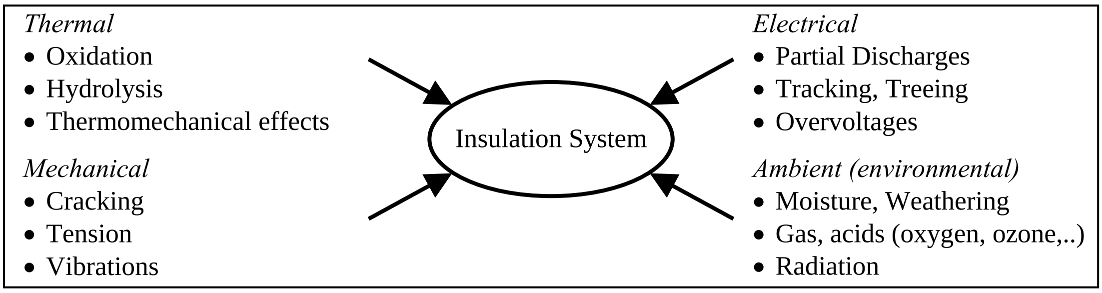

Fig. 1: Ageing stresses (according to IEC 60505)

These stresses, individual or combined, will cause ageing i.e. an irreversible change of the properties of an insulation system.

2.1 Thermal Ageing Model

The thermal ageing in insulating materials is complex and the mechanisms vary in different materials and under different service conditions.

To a first approximation, the oxidation process can be expressed by the Arrhenius rate law. The life of the insulation (L, in hours) is related to the temperature (T, in °K) by

$$L = A \cdot \exp\left(\frac{B}{T}\right) \qquad (2.1)$$

where A and B are assumed to be constants. As a rule of thumb, the life of the winding will decrease by 50 % for every 10 °C rise in temperature. It is evident that, the higher the temperature, the shorter is the life expectancy of the insulation. The Arrhenius law is the basis of all accelerated ageing tests which are used to estimate the thermal life of a winding and is also used to define the insulation thermal classes. [1]

2.2 Electrical Ageing Model

In the presence of partial discharges, the single electrical ageing is mostly represented by the inverse power model (formula 2.2).

$$L = k \cdot E^{-n} \qquad (2.2)$$

Plotted on log-log graph paper, the voltage endurance data will result in a straight line according to the inverse power model. Sometimes the exponential model (formula 2.3) is used.

$$L = a \cdot \exp(-bE) \qquad (2.3)$$

Both empirically deduced models describe how the life of the insulation L (in hours) is depending on the electrical field strength E (in kV/mm) and experimentally determined factors k, n, a and b.

Extrapolation to low-voltage stresses for both models can result in very large differences in the predicted time-to-failure. Below a certain threshold electrical stress (partial discharge extinction voltage) ageing may no longer take place. This lower threshold field strength E_t can be accounted for by dividing equations 2.2 and 2.3 by $E\text{-}E_t$. [1]

2.3 Multifactor Ageing Model

For describing combined thermal-electrical ageing, several different models can be found in literature. Most frequently cited are the empirical model given by L. Simoni and the physical model by J. P. Crine.

Simoni’s model (formula 2.4) is obtained by multiplication of the life models for single thermal and single electrical ageing (inverse power model) together with a correction term.

$$L(T,E) = L_0 \cdot \exp\left(-B\Delta\left(\frac{1}{T}\right)\left(\frac{E}{E_0}\right)^{-N}\right), E \geq E_0 \qquad (2.4)$$

L_0 is time-to-breakdown at room temperature and $E=E_0$, $N=n-b\Delta(1/T)$, n is a constant and $\Delta(1/T)=1/T-1/T_0$. [1]

3 Normative Determining Factors

In standardisation, there is a distinct difference between the thermal endurance of electrical insulating materials (EIM) including simple combinations of such materials and the performance of whole electrical insulation systems (EIS). Figure 2 shows a survey of the various different IEC standards related to the thermal evaluation of EIM and EIS and the linkage to the insulation systems for rotating electrical machines.

The thermal evaluation process, as well as a choice of test and end-point criteria for single insulating materials, is clearly defined by IEC 60216 standard (e.g. 10 % loss of mass for impregnating compounds and varnishes).

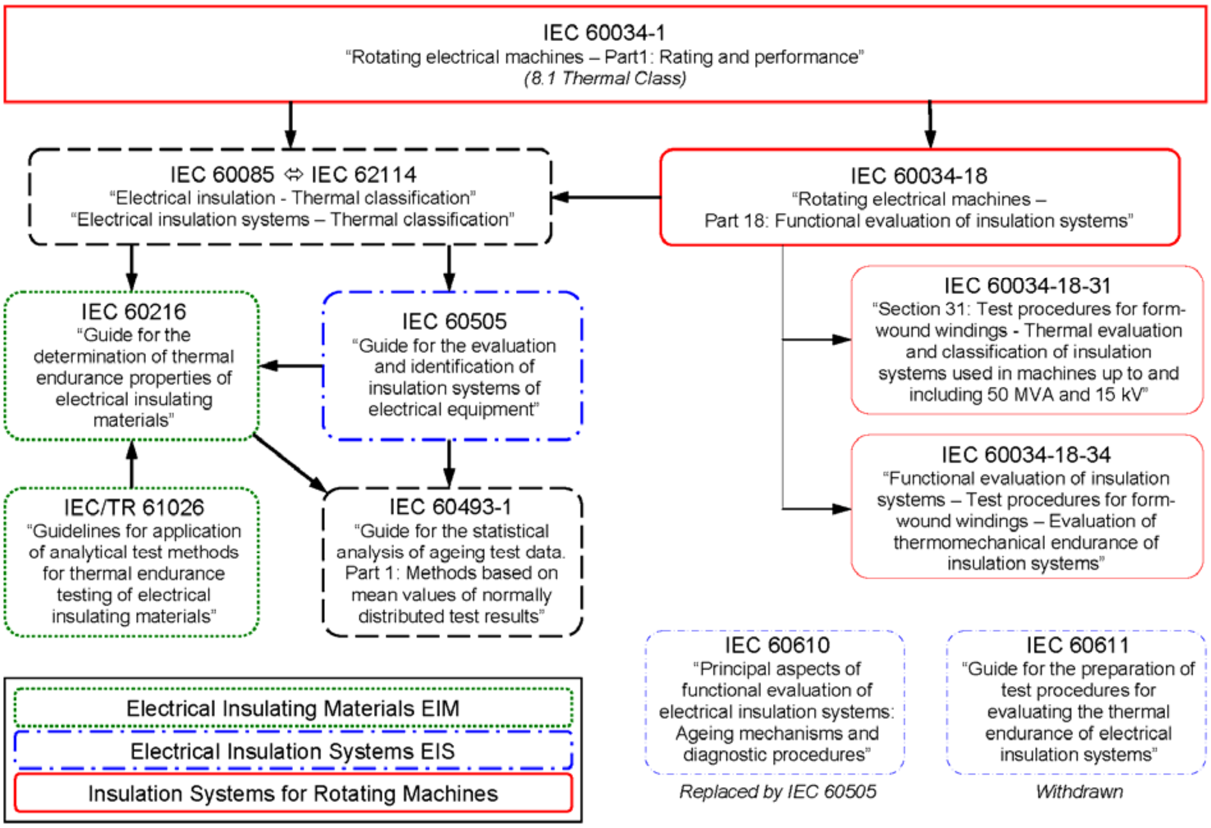

Fig. 2: Survey of IEC standards related to the thermal evaluation of EIM and EIS

Electrical insulation systems are structures containing one or more insulating materials with associated conducting parts. The thermal class of an EIS can be different from the thermal endurances of the individual EIM it contains. An example of thermal upgrading is Nomex - PET film - Nomex 3-ply laminate (e.g. ISONOM NMN, NOMEX is a registered trademark of DU PONT) used as slot liners in low voltage motors. PET film is rated thermal class 130, but in combination with Nomex the laminate has thermal class 155 according to IEC and even 180 according to UL 1446 standard. Similarly the PET-mica insulating tapes used for the mainwall insulation of high voltage machines are thermal classified as 155 (e.g. CALMICA or POROFOL).

However, the opposed effect also can occur. Problems of incompatibility between EIM could decrease the overall thermal class of the system. [2]

A comprehensive thermal evaluation of the EIS of rotating machines should not only cover the mere thermal classification but also the thermomechanical and combined thermal and electrical endurance (complete IEC 60034-18 series).

4 Complexity of the Thermal Evaluation of Rotating Machine EIS

The insulation system for windings of high voltage machines typically includes materials for stack preconsolidation, single conductor insulation, mainwall insulation (e. g. different mica tapes in slot and overhang part in resin rich technology), outer and end corona protection system and additional materials (impregnating resin in VPI technology, spacer, slot wedges,..).

For the thermal evaluation of this insulation system for form-wound windings comprising numerous different materials a formette construction is proposed in IEC 60034-18-31. This test model should embody all essential elements of the winding. In thermal ageing sub-cycles, the test specimens are exposed to elevated temperatures for accelerated thermal ageing. [3]

The maximum ageing temperature selected for the thermal class 180 may be 240 °C. This means, that all parts of the winding including corona protection system and winding overhang are subjected to that very high thermal stress. Presently there is no corona protection system (even though it is rated 180) which can withstand such high temperatures and operate properly after exposure. Apparently the IEC 60034-18 standards series is not providing any procedure for the thermal evaluation of insulation systems regarding the performance of outer and end corona protection coatings.

The temperature of the winding overhang in operation is in many cases lower than in the slot portion. So the overhang insulation as well as overhang sealing and supporting components are aged needlessly higher than compared to materials in the straight part of the winding.

The dimensions of the formette construction are not standardised and have to be adapted to the machine design for which the insulation system is designated. Different models may be employed to cover the range of AC and DC machines with different winding and cooling systems. Comparability between these models is not given.

A number of diagnostic tests including a mechanical, a moisture, a voltage and other diagnostic tests is proposed in IEC 60034-18-31 but not all of the tests need to be conducted necessarily. However large motor OEM’s only accept the thermal evaluation if all tests have been applied in the named order. Only if a mechanical and a moisture test are applied, the power-frequency voltage test at $2 \cdot U_N$ will lead to a realistic end-point. For the evaluation of the insulation systems of large generators, humidity is of little relevance and hence the test procedure according to IEC 60034-18 is not very appropriate.

A number of other diagnostic tests like measurement of the insulation resistance, loss tangent or partial discharges are mentioned, but no end-point criteria are given.

The evaluation procedure is comparative; this means that the performance of a candidate insulation system is compared to that of a reference system with proven service experience. By extrapolating the Arrhenius graph of the reference system to the class temperature, the mean test life is obtained (cp. 20000 h defined in IEC 60216). If the candidate system shall have the same thermal class, the same test life has to be obtained. By advisedly selecting the reference system, the thermal class of the candidate system can be influenced.

5 Conclusions

Compared to the thermal evaluation of insulating materials, the evaluation of high voltage insulation systems of rotating machines has many determining factors. IEC standards only partly account for that complexity and some open questions remain, such as definition of test procedures for the corona protection system or consideration of the temperature situation in the winding overhang.

5 References

[1] A. C. Gjerde: “Multifactor Ageing Models – Origin and Similarities”, IEEE Electrical Insulation Magazine, Vol. 13, Issue 1, 1997

[2] IEC 60085: “Electrical insulation - Thermal evaluation and designation”, 2007-11

[3] IEC 60034-18-1: “Rotating electrical machines - Part 18: Functional evaluation of insulation systems - Section 1: General guidelines”, 1992-02, Amendment 1996-11

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