

The evaluation of the condition of high-voltage system with using accelerated voltage time tests and design of main wall insulation thickness for stator bar of generator stator winding

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Abstract — Assessment of the optimal thickness for mainwall insulation tube in the slot part of the stator bar belongs to an important item in the design of the insulation system from view of the functionality and operational reliability of the rotating machines.

Keywords— *mainwall insulation thickenss, insulation system, voltage endurece test, regression line, voltage-time test, stator coil, life time curve, Student distribution*

I. INTRODUCTION

The purpose of this article is to introduce the experience from evaluation of the accelerated destructive tests as a relevant tool for the design. The initial tool of the method is to obtain the life endurance curves, it means the regression lines

$$E = a - b \cdot \log T \quad (kV/mm; s) \quad (1)$$

established by the least squares method from evaluation of the voltage-time tests. In the article there is mentioned an additional processing of the regression lines which with usage of the statistical methods leads to determination of the insulation tube thickness for stator slot part for given nominal voltage. In the article there is also described an importance of the diagnostic, voltage withstand, interoperation tests provided in purpose to check the insulation system quality during the manufacture on a real stator coil.

II. THE WAY OF OBTAINING AND EVALUATION METHOD FOR THE VOLTAGE-TIME TESTS

A. Providing of the voltage-time tests

The goal of the tests is to obtain the time to the breakdown at several suitable chosen voltage levels for chosen number of the samples. The tests are mostly done on trial samples – on models of the real insulation wall in

slot part, or on sections cut from real stator coils. The generally acknowledged criteria for voltage endurance is a KEMA standard (in Europe) : 10 hours at $3U_n$ and 1000 hours at voltage $2U_n$. According to IEEE 1043 standard it is 400 hours at voltage $2U_n+2$ kV (in USA, Canada). Usually there is the requirement for 90% of samples which should meet these criteria. Time is measured (in seconds) to the breakdown for applied AC voltage 50Hz, effective value U (kV). The value of the el.stress E (kV/mm) is given for the net insulation thickness:

$$E = U/d \quad \left(\frac{kV}{mm} \right) \quad (2)$$

The value $\log T$ in the equation (1) is a common logarithm of the time to breakdown (s).

B. Method of evaluation

The basic principal for the assessment of the optimal main wall insulation thickness is the knowledge of the regression lines for two insulation thicknesses. And the presumption that there exists a defined linkage between the breakdown voltage U_p and insulation thickness. For our purpose there was used a general formula given for example at [1]:

$$U_p = G \cdot d + A \cdot \sqrt{d} \quad (kV/mm) \quad (3)$$

where G , A are constants characterising a particular insulation system. At the same time the optimal thickness must meet the requirements for safety operation. For this intent we work with the statistical methods during evaluation of the accelerated voltage endurance tests. The statistical methods respect the dissipation of the independent stochastic variables, it means values $\log T$ at suitable chosen values of the electric stress E . The size of the individual dissipation \hat{s} at given correlative coefficient r for the regression line $E = a-b \cdot \log T$ obtained by the least squares method is established by an equation (4) :

$$\hat{s} = s(\log T) = s \cdot \log T \cdot \sqrt{1 - r^2} \quad (4)$$

where $s(\log T)$ is the standard sampling deviation of values $\log T$.

In context of the mentioned requirements for safety it is possible to use a Student distribution to calculate the border line at chosen probability P . For the Student distribution there is a degree of freedom $\nu = (n - 1)$, where n is a count of the file. The line displacement at probability level $P=50\%$ (it is the calculated regression line), is given for a chosen confidence limit by equation (5):

$$\Delta \log T (P, \nu) = \hat{s} (\log T) \cdot t_p(\nu) \quad (5)$$

where $t_p(\nu)$ is a quantile of the Student distribution for chosen reliability level. We choose the reliability level 99% or 99.9%. In respect to the safety design of the optimal insulation thickness at respecting KEMA criteria we choose the criteria related to the $3U_n$ voltage. It means the el.stress $E = 3U_n/d$ at requirement for time to breakdown $T = 10 \text{ hours} = 36000s$; $\log(T) = 4,5563$. This criteria in respect to the border line slope is rather strict than the criteria for $2U_n$: 1000 hours [2]. Because the nominal voltage was derived as 1/3 of the interval for a bottom limit of breakdown voltage values after 10 hours of the voltage exposition, it was for deriving of the nominal voltage U_n assessment $U_n = f(d)$ used a general relation (3), then according to the formula (3) we can write for assessment of the thickness for given U_n :

$$U_n = G \cdot d + A \cdot \sqrt{d} \quad (kV/mm) \quad (6)$$

We work with results for both net insulation thicknesses d_1, d_2 we have two files of the values. We calculate two regression lines at reliability level $P=50\%$. For these regression lines we calculate the boarder lines at probability $P=99.9\%$:

$$E_1 = a_1 - b_1 \cdot \log T ; E_2 = a_2 - b_2 \cdot \log T \quad (7)$$

The lines cross in a point $\log T_x ; E_x$

For $\log T = 4,5563$ at knowing constant a and b of the lines we can establish E_1, E_2 and for requirements $U_n = \frac{E \cdot d}{3}$ we can establish U_{n1} and U_{n2} for which we apply the formula (6). We receive a system of 2 equations, after solving we receive the constants G, A . The knowledge of these constants leads to a possibility to assign new chosen thickness d_3 to the maximal nominal voltage U_n . The knowledge of assigning U_n to d_3 implies the possibility of assessment

$$E_{n3}(d_3) = \frac{3U_n(d_3)}{d_3}, \text{ resp. } E_{n2}(d_3) = \frac{2U_n(d_3)}{d_3} \quad (8)$$

and possibility to assess the coefficients a_3, b_3 of the line $E_3 = a_3 + b_3 \cdot \log T$ for thickness d_3 . This newly obtained line has got a shared intersection point with both lines according to the formula (7).

C. Usage of the metod for assesment of the tehoretical voltage endurece curve for any thickness parameter d

This fact mentioned in section B leads to the possibility to deduce a direct calculation of relationship between el.stress

E and $\log T$ for different thickness d figuring in equation as a parameter: $E_d = f(\log T, d)$.

There are two conditions consequently for assesment above mentioned dependancy: the mandatory point required by KEMA standard for 10 hours : $\left[\log(36000) = 4,5563; E_{n3} = \frac{3 \cdot U_{n3}}{d} = \frac{3 \cdot (G \cdot d + A \cdot \sqrt{d})}{d} \right]$ and the point for the shared intersection point. Thanks to knowledge of two regression lines according to formula (7) we can establish $[\log(T_x); E_x]$. It enables to calculate the coefficients a_d and b_d for equation relating to insulation for arbitrarily chosen insulation thickness.

$$E(d) = a(d) - b(d) \cdot \log T \quad (9)$$

After substitution in the equation (7) relating to coefficients $a(d)$ and $b(d)$ we get the searched equation for the course $E_d = f(\log T, d)$, where d is the parameter:

$$E_d = \alpha + \beta \cdot \sqrt{d} + \gamma \cdot \frac{\log(T)}{\sqrt{d}} + \delta \cdot \log(T) \quad (10)$$

This relation is an equation of the border line at chosen probability level and for chosen thickness d of the tested insulation system. For condition of 10 hours for $3U_n$ voltage, i.e. $\log T = \log(36000) = 4,5563$, we can wrtire:

$$E_d = \alpha + \beta \cdot \sqrt{d} + \frac{\bar{\gamma}}{\sqrt{d}} + \delta \quad (11)$$

where

$$\bar{\gamma} = \gamma \cdot \log(T) \bar{\delta} = \delta \cdot \log(T) \quad (12)$$

D. Example of the method for particular insulation system

For given insulation system the times to breakdown were obtained during the accelerated voltage endurance tests for net insulation thickness $d_1 = 2.2mm$ and $d_2 = 3.5mm$. With usage of least squares method we get the regression equations of the regression lines (and their coefficients a, b) at probability level $P=50\%$. See Fig.1

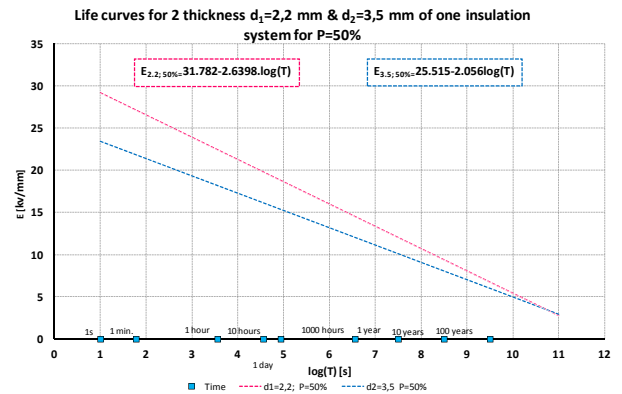


Fig. 1 Life time curves measured for two thickness and $P=50\%$

Above mentioned method in paragraph B we recalculate the chosen reliability level $P=99.9\%$ with usage of formula (4) and (5). The lines for $P=50\%$ and $P=99.9\%$ are displayed in Fig.2.

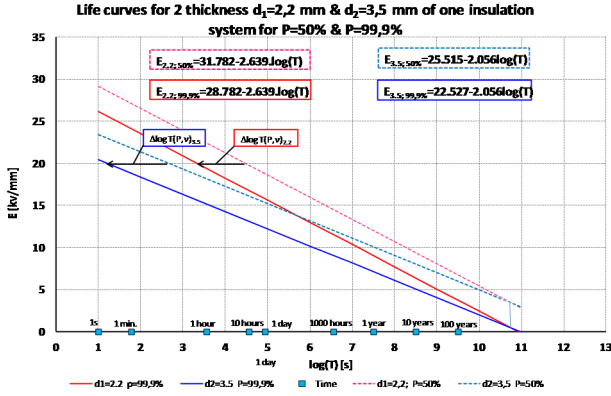


Fig. 2 Life time curves for two thicknesses and two probability levels $P=50\%$, $P=99.9\%$

For probability $P=99.9\%$ and for time $T = 10 \text{ hours} = 36000\text{s}$; $\log(T) = 4.5563$ we get:

$$E_1 = a_1 - b_1 \cdot \log T = 28.728 - 2.6398 \cdot 4.5563 = 16,8 \text{ kV/mm} \quad (13)$$

$$E_2 = a_2 - b_2 \cdot \log T = 22.527 - 2.056 \cdot 4.5563 = 13,16 \text{ kV/mm} \quad (14)$$

With application of the requirement 10 hours at $3U_n$, then $3U_n = E \cdot d$ and formula (6) for both thicknesses we get equation system:

$$U_{n1} = G \cdot 2.2 + A \cdot \sqrt{2.2} = 12.321 \text{ kV} \quad (15)$$

$$U_{n2} = G \cdot 3.5 + A \cdot \sqrt{3.5} = 15.353 \text{ kV} \quad (16)$$

Solution of the equations (15) and (16) is obtaining constants $G = -0.258$; $A = 8.69$. The intersection point: $[\log(T_x); E_x] = [10.794; 0.336]$. At this moment it is possible to assign the voltage U_n for arbitrarily chosen insulation thickness. For example for choice $d_3=2.5 \text{ mm}$ we get according to formula (6):

$$U_{n3} = -0.258 \cdot 2.5 + 8.69 \cdot \sqrt{2.5} = 13.094 \text{ kV} \quad (17)$$

For this chosen thickness with respect of condition (8) for equation $E_3 = a_3 - b_3 \cdot \log T$ it is possible to establish the constants $a_3 = 26.954$ and $b_3 = 2.465$ for a theoretic life endurance line at probability $P=99.9\%$ for insulation thickness 2.5mm . Take into consideration other two conditions mentioned in paragraph B, i.e. the mandatory point required by KEMA standard for 10 hours and the shared intersection point $[\log(T_x); E_x]$ it is possible to establish a direct dependency of the el.stress trend according to equation (10) and to find:

$$\alpha = -1.587; \beta = 45.113; \gamma = 4.18; \delta = 0.178.$$

We can write the equation (10):

$$E_d = -1.587 + 45.113 \cdot \sqrt{d} + 4.18 \cdot \frac{\log(T)}{\sqrt{d}} + 0.178 \cdot \log(T) \quad (18)$$

For insulation thickness lower than d_1 and higher than d_2 is the mentioned equation valid only at presumption of approximately the same correlate coefficient as obtained from experimental measurements.

For the two life endurance curves obtained from measurements it is possible to draw a line for $d_3 = 2.5 \text{ mm}$ as shown on Fig.3. In Fig.3 there are also displayed the lines KEMA Standard for U_n assigned to each individual system for given thickness:

$$U_{n1} = \frac{E_1 \cdot d_1}{3} = 12.321 \text{ kV}; \quad U_{n2} = \frac{E_2 \cdot d_2}{3} = 15.353 \text{ kV};$$

$$U_{n3} = G \cdot d_3 + A \cdot \sqrt{d_3} = 13.094 \text{ kV}.$$

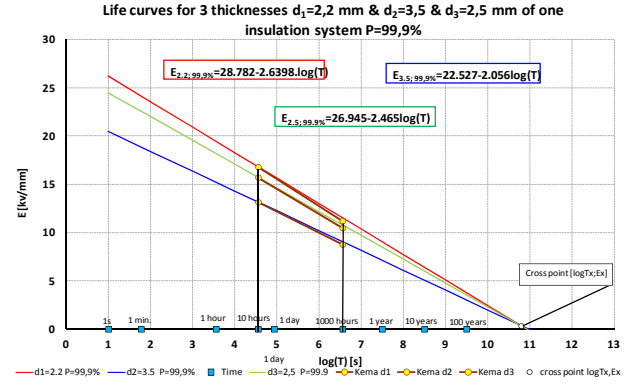


Fig. 3 The calculated life time curve for chosen insulation thickness d_3 and $P=99.9\%$ and other two life time measured curves

With usage of equation (18) it is possible to assign the chosen thickness to the parameters, operational stress and nominal voltage. The table 1 and Fig.4 give a summary for nominal voltages U_n from 11 kV to 16.5 kV.

TABLE I. CHOSEN THICKNESS AND ASSIGNED PARAMETERS

| d_n [mm] | $a(d)$ | $b(d)$ | E_{op} [kV/mm] | U_n [kV] |
|------------|--------|--------|------------------|------------|
| 1.8 | 32.039 | 2.937 | 3.590 | 11.194 |
| 2 | 30.313 | 2.777 | 3.398 | 11.773 |
| 2.2 | 28.829 | 2.640 | 3.233 | 12.321 |
| 2.4 | 27.534 | 2.520 | 3.089 | 12.842 |
| 2.6 | 26.391 | 2.414 | 2.962 | 13.340 |
| 2.8 | 25.374 | 2.320 | 2.849 | 13.817 |
| 3 | 24.460 | 2.235 | 2.747 | 14.276 |
| 3.2 | 23.632 | 2.158 | 2.655 | 14.718 |
| 3.4 | 22.879 | 2.089 | 2.572 | 15.145 |
| 3.6 | 22.190 | 2.025 | 2.495 | 15.558 |
| 3.8 | 21.556 | 1.966 | 2.425 | 15.958 |
| 4 | 20.970 | 1.912 | 2.359 | 16.346 |

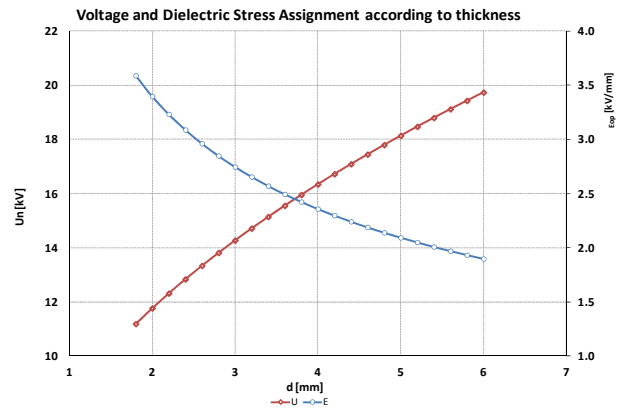


Fig. 4 Dependency of the el.sterrs and nominal voltage on the insulation thickness

III. TESTS, OPTIONS OF VERIFICATION AND INDICATORS OF QUALITY FOR INSULATION SYSTEM

The several options for verification of design new insulation system have relation to the accelerated tests of aging process or qualitative parameters of insulation system. The accelerated tests (by voltage, temperature, mechanical or combined stress) are performed in first step on short straight sections and the results are compared with reference insulation system (functional and verified). The qualitative parameters are measured during aging of insulation system in interval for evaluation on logarithmic axis. The tests are performed on production-technologic part of winding with new insulation system in next step, in this place the tests are divided on two groups - the first group is time-consuming and where the evaluation is in time base in accordance with KEMA or IEEE standard, and the second group is demanding on voltage power supply - the tests of insulation system continue to breakdown - random test in accordance with standard EN 50209 [3]. This test is to disposal for the customer, which gives option on review of insulation system.

We have the possibilities on verification of quality for individual parts, function groups or stator winding during production of insulation system, but these possibilities are different for used production technology - here is a great difference between technology Resin-rich and method of global VPI. Both technologic process must declared insulation system without defect for the customer with withstand high voltage test in accordance with standards EN 60034-1 and IEC 60-1. The voltage is determined in standard EN 60034-1 in accordance with formula (19) and the time waveform of testing voltage is determined in standard IEC 60-1.

$$U_{tv} = 2 \cdot U_n + 1 \text{ (kV)} \quad (19)$$

Various possibilities in testing of insulation system are given the difference between both technologies of production. The VPI insulation system has limited possibilities of testing during producing and the discarding or replacement of part of winding is not almost possibly. The system Resin-rich is in this view better than global VPI and we can test the insulation system during production. In the first line it is testing of individual stator coils or stator bars and on the base of measured quality parameters or statistical variables we can perform selection and discarding of faulty pieces. These parameters will be the dissipation factor $\tan \delta$ measured in accordance with EN 50209, maximal limit for quantity of partial discharges measured in accordance with standards EN 60270 and EN 60034-27 or statistical deviation from average of measured parameters. This testing of insulation system parts we supervise and control the required parameters of insulation system during production of winding, so than complete winding is in accordance to standards and requirements of a customer.

On complete and tested generator the producer must perform the withstand high voltage test in accordance to standards (written higher), so than he can declared the insulation system without defects and the reliable insulation system. The producer should offer and recommend addition appropriate complementary tests.

These tests should have additional value for the customer in wider knowledge about insulation system of bought generator and these tests are the start line of diagnostic parameters for the future evaluation of generator life time. The recommended measurements and parameters are absorption characteristic, polarization index, dissipation factor $\tan \delta$ and capacitance of winding, measurement of partial discharges and measurement of leakage current. These monitored parameters should be measured in regular intervals during life time of generator, because any marked change of some parameter can show on failure or damage of insulation system. The reliability and function of insulation system is verified with prophylactic withstand high voltage test.

IV. CONCLUSION

The article strives to interpret how to design the optimal and safety thickness of the insulation system of the stator coils. The base of this way of design is the knowledge of the lifetime curve trend for two thicknesses of certain insulation system that are treated by means of statistical methods and used for assessment of the proper thickness according to the nominal voltage. This process is based on voltage-time accelerated tests. Additional non-destructive and destructive tests are important even for verification of quality during manufacturing of stator winding.

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