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Insulation Life Tests of Multiple Insulated Wire Cables in Presence of High Frequency and High Temperature

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Abstract: The behaviour of insulated copper wire windings in presence of power ac voltage and relatively high temperatures from the point of view of the insulation life is reasonably well known.
However, the introduction of both modern multiple insulated wire cables and high frequency PWM-like supply voltages can give rise to a lower insulation life than in the previous case. A research program has been rigged to investigate two aspects of this problem. The first aspect regarded a comparison between the life curves behaviour of same twisted pairs enamelled wire specimens in ac high frequency voltage conditions and the life curves in PWM-like voltage conditions: the results evidenced that the above agings are not described by the same mathematical model.
The second aspect regarded the study of a testing procedure to qualitatively estimate, in a relatively short time, the weight of the enamelled wire insulation endurance on the long term behaviour of a full insulation winding (represented by segments of an actual winding). The reported results of specific tests evidenced a way to achieve such a goal, therefore to save testing costs and time during the development of an insulation of this type.

Introduction

The application of high frequency steep fronted square voltages has lead to increasing problems relevant to the insulation system in electrical machines supplied by inverter [1,2,3].
Different authors assumed that four main ageing acceleration factors play a role in the degradation process: the electric field (or voltage), the rise time, the frequency and the temperature [4,5].
At the Electrical Engineering Dept. laboratory, a research program is under way. Two goals are being pursued:
a) referring to specimens (twisted pairs) of enamelled insulated wires, to compare the life-curves of such specimens when subjected to ac sinusoidal voltage waveforms with the life-curves of the same specimens when subjected to square-wave (PWM-like) voltages;
b) referring to full windings insulation, to study a testing procedure able to evidence the role of the enamel insulation with respect to the behaviour of the full insulation.
The results of a first study on twisted pair specimens of enamelled insulated wires, subjected to ac sinusoidal voltage waveforms at different frequencies and amplitudes and at different temperatures, have been presented in [6]. As that work evidenced a link (model) between the test parameters and the duration of the samples, a similar model was sought even at this second stage, where a set of test parameters was initially devised (for instance, a 40 kHz switching frequency has been assumed, while peak-to-peak voltages, fundamental frequency and temperature were varied). As regards goal b) a sample of a full insulation winding (several single enamelled wires) has been selected and a set of specific test parameters has been devised too.

Specimens and test setup

The ageing tests were performed on two different kind of specimens: a) on twisted pair specimens obtained from enamelled copper wires (temperature class 200 polyimide-imide, double layer), prepared following the IEC 851-5 procedure; one leg of the twisted pair was energised and the other one was grounded. The test voltage was applied till the enamel insulation failed and the time-to-breakdown was recorded; b) on windings formed by several enamelled wires (same as the ones used for the twisted pair specimens) and then insulated by an insulating tape and impregnated.
The adopted test configuration was obtained referring to IEC 851-5 procedure.
The enamel was removed at one end of a sample 500 mm long, then the sample was folded by a 50 mm diameter mandrel and set in a box surrounded by small metal marbles. The test voltage was applied to the cleaned end of the sample and the grounded box.

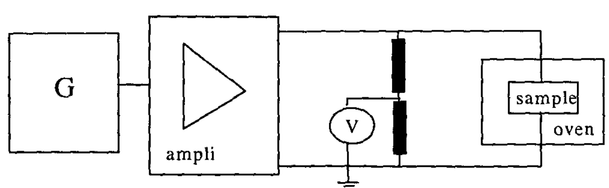

Figure 1 - Test set-up circuit

The test voltage was supplied by a linear amplifier with a 60 dB gain, a maximum input voltage of 6 V peak-to- peak and a bandwidth of 20 Hz-40 kHz at the maximum output voltage amplitude and up to 3 MHz at 1 kV peak to peak output voltage amplitude. The linear amplifier was necessary in order

to obtain voltage waveforms PWM- like and to enable an easy setting of amplitude, base frequency, duty cycle and switching frequency. For instance, in this case, PWM-like waveforms were selected with different base frequencies (10, 5 and 3 kHz), different peak to peak amplitude (from 2.2 to 4.5 kV) and with rise time of 1 kV/µs, switching frequency of 40 kHz and duty cycle of 50%.
The applied voltage was measured through a high-frequency resistive divider. A specimen failure triggers a protective relay, which records the time-to-breakdown. Each specimen, before applying the test voltage is pre-heated in oven at the test temperature.

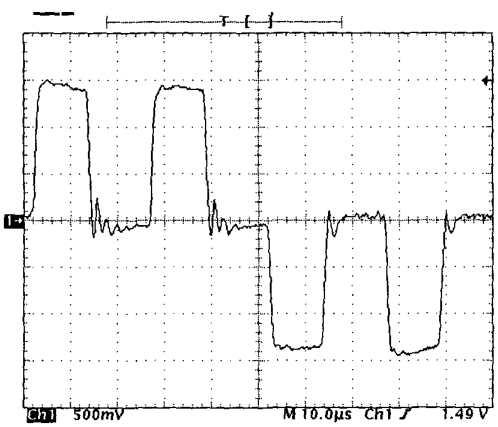

Figure 2 - Example of an applied waveform

Experimental Results

The selection of the parameters for the tests on twisted pairs was made with reference to the previous work. In that case [6], the same twisted pairs, when subjected to ac voltages between 600 and 2000 V, at frequencies between 5 and 1,5 kHz at temperatures between 20 and 200 °C, showed the following experimental relation:

$$D(V, \theta, f) = k(f, \theta)\, V^{-n(\theta)} \qquad (1)$$

Where D is the time to failure, θ is the test temperature, V and f are the amplitude and the frequency of the applied test voltage. In (1) k and n are two parameters dependent on the test conditions and on the tested material. Namely, in that case, (1) translated in:

$$D(V,\theta,f) = \frac{1.026 \cdot 10^{21} \cdot \theta^{-3.1} \cdot V^{-4.7864 \cdot \theta^{-0.1248}}}{f} \qquad (2)$$

where the duration is inversely proportional to the frequency.

Therefore, in the present case, i.e. for the PWM-like waveforms, three different peak-to-peak voltages (3820, 3000, 2200 V), three base frequencies (10, 5, 3 kHz) and three test temperatures (100, 150, 200°C) were selected (actually, at 200°C, just the 10 kHz frequency was adopted). All other parameters (rise time, switching frequency and duty cycle) were kept constant. Groups of 3 specimens were tested: the relevant average lifetime is reported in Table 1.
The curves in Figs. 3 and 4, obtained assuming model (1), show that in the present case, the parameter n would not be dependent neither on either θ or on f, while the parameter k appears to be dependent on both θ and f.

Table 1 - Twisted pair wires: test conditions and average lifetimes

voltage [V]	frequency [kHz]	temperature [°C]	lifetime [s]
3820	10	100	172
3000	10	100	647
2200	10	100	1494
3820	10	150	129
3000	10	150	342
2200	10	150	1026
3820	10	200	126
3000	10	200	216
2200	10	200	855
3820	5	100	321
3000	5	100	651
2200	5	100	2778
3820	5	150	159
3000	5	150	483
2200	5	150	1917
3820	3	100	360
3000	3	100	789
2200	3	100	3966
3820	3	150	282
3000	3	150	507
2200	3	150	2739

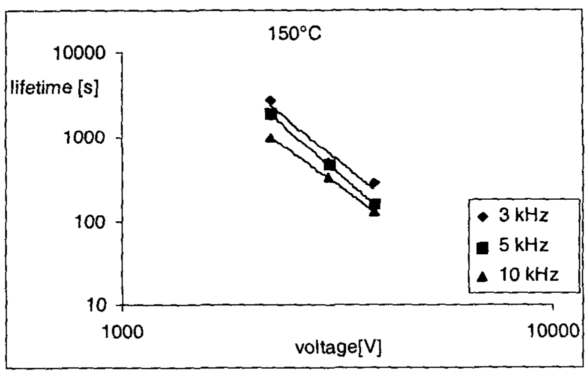

Figure 3 - Bilog plot of test voltage vs. duration at 150 °C: parameter frequency

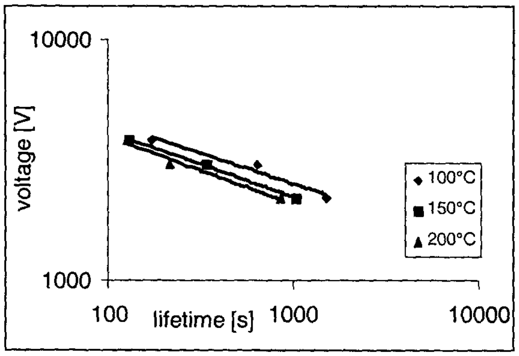

Figure 4 - Bilog plot of test voltage vs. duration at 10 kHz: parameter temperature

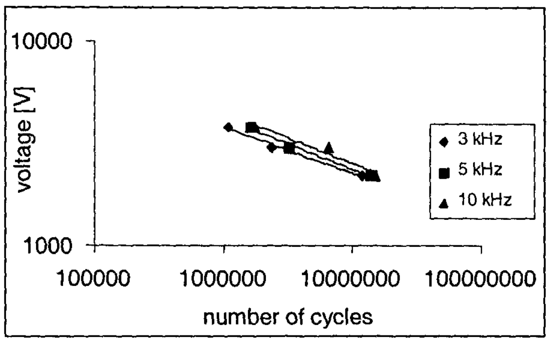

Figure 5 - Test voltage vs. number of cycles to failure at 100 °C: parameter frequency.

Figure 5 evidences another difference from the ac tests: in this case the curves "test voltage vs. number of cycles to failure" (at a fixed temperature and different frequencies) do not overlap. This means that the lifecurve cannot be expressed by a relation like the following one:

$$D(V,\theta,f)=[k'(\theta)\,V^{-n\ (\theta)}]/f \qquad (3)$$

where the duration is inversely proportional to the test (fundamental) frequency. This fact could partly be explained by the number of peaks (max and min) per period Np: in the ac tests it did not vary with changing frequency, in these PWM-like tests this number varies, because the switching frequency has been kept constant. Np can be linked to the effect of the partial discharges, which, were always active, at the here tested voltages. As the second goal was concerned, a simple series of tests were run on the sample of winding previously described. Also in this case groups of 3 samples were subjected to a 10 kHz fundamental frequency voltage at 100 °C (40 kHz switching frequency).While the average times-to-breakdown are reported in Table 2, the life curves at similar test conditions of both twisted pair specimens and full winding insulation sample are reported in Fig. 6.

Table 2 - Samples of the winding: test conditions and average times to breakdown

voltage p-p [V]	frequency [kHz]	temperature [°C]	lifetime [s]
4500	10	100	5054
3820	10	100	51570
3600	10	100	294360

Comments

The first series of tests, as shown above, has evidenced that, at least in presence of partial discharges, it is not always possible to directly extrapolate a phenomenological model found valid for ac tests (although run at relatively high frequency) to cases where PWM-like voltages are applied. Besides it seems worth to note that, in the latter cases, the behaviour of the various life curves does not lend itself to an easy and precise modelling: probably, as mentioned, the effects of the partial discharges are affecting the ageing process in different ways.

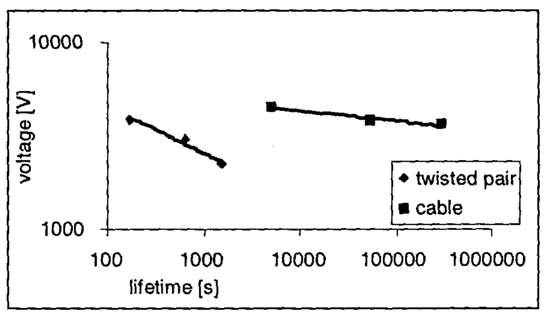

Figure 6 - Bilog plot of times-to-failure vs. applied voltage for twisted pair specimens and for full insulation samples

The study about the testing procedure (goal b) of the present research program) for full insulation of windings composed of enamelled wires offers some useful, although qualitative, elements.
For instance, a comparison between the results of similarly performed tests can be based on the analysis of Fig. 6 .
This way, it appears that the presence of the enamel insulation (a "weak component", as demonstrated by its life curve) does not excessively affect the performance of the full insulation sample.
Therefore the implementation of testing procedures where the life curve of a full insulation vs. the life curve of some of its weakest insulating components is compared (running tests in very similar conditions) can offer a way to comparatively

evaluate the weight of different wire insulation performances on the highest full winding insulation performance.
This way cost and time savings along the design and laboratory testing stage can be achieved.
However an electrical insulation system design should take in account that in applications where the "weak component" is directly stressed lower performances are to be expected.

Conclusions

A research program aimed at two different goals has been implemented. The discussion of the relevant results has evidenced that:

a) the results of tests on twisted pairs of enamelled wires run at ac frequency do not always favourably compare with results obtained applying PWM-like voltages
b) it is possible to devise parallel testing procedures useful to evidence the weight the enamelled wires insulation on the performance of full winding insulation.

Acknowledgements

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