

Lifespan Modeling of Insulation Materials for Low Voltage Machines: films and twisted pairs

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Abstract- The aim of this paper is to present some improvements of the method for modeling the lifespan of insulation materials in a partial discharge regime. The first step is based on the design of experiments which is well-known for reducing the number experiments and increasing the accuracy of the model. Accelerated aging tests are carried out to determine the lifespan of polyesterimide insulation films under different various stress conditions. A lifespan model is achieved, including an original relationship between the logarithm of the insulation lifespan and that of electrically applied stress and an exponential form of the temperature. The significance of the resulting factor effects are tested through the analysis of variance and, response surface takes into account some second order to improve its accuracy. Finally, the model validity is tested with additional points which have not been used for modeling.

Index terms— dielectrics, insulation, accelerated aging, lifespan estimation, condition monitoring, modeling, response surface, analysis of variance, films, twisted pairs

1. INTRODUCTION

Low voltage electric machines are increasingly submitted to heavy electric constraints and their lifespan becomes nowadays a concern. Among many papers, [1] have reported that stator-winding insulation is one of the weakest components in a drive (around 40% of failures). Materials involved in electric ageing affect the insulation system lifespan. Many operating factors such as voltage, frequency, temperature, pressure, etc. could have a dramatic effect as these stresses can synergize as shown in [2]. The existing models of degradation or of lifespan differ slightly from one paper to another but they are all based on physics and include some factors which are specific to the material or the aging mechanism. As examples, [3]-[4] include the physical, thermal and electro-mechanical aspects of the electrical aging process. Additionally, the choice of the lifespan forms remains critical for model accuracy. Various forms can be found in different works such as [5] where they mainly involve a log-based relationship for frequency and voltage and an exponential form for the temperature. Nevertheless, there is no comprehensive model for insulation lifespan prediction under different combined stresses and this phenomenon remains complex and difficult to understand and to model, especially with PWM supply.

Experimental tests are necessary to assess lifespan modeling but full aging tests for all the factors involved in the aging process under nominal conditions could be time consuming. As a consequence, accelerated aging tests which are about to speed up the degradation, are generally performed in order to study and predict the lifespan. The “Design of Experiments” (DoE) [6] was helpful in many cases either for optimization or modeling purposes. A set of 8 tests are carried out for each combination of the stress factors (Voltage, Temperature and Frequency). To be more cost effective, this paper tries to reduce this number of tests and to check whether the results remain statistically significant or not and Analysis of Variance (ANOVA) will be employed.

2. SYSTEM DESCRIPTION AND BASIC DOE

The testbench itself and the tested insulation materials have been fully described in [7]. It consist of steel plates coated with polyesterimide (PEI - thermal class: 180°C) films which are widely used in rotating machine insulation systems (15cm x 9cm with a 90µm coating). Moreover, twisted pairs (entwined copper cords, coated by an insulator varnish) are also studied while they are expected to behave similarly than the stator-winding insulator.

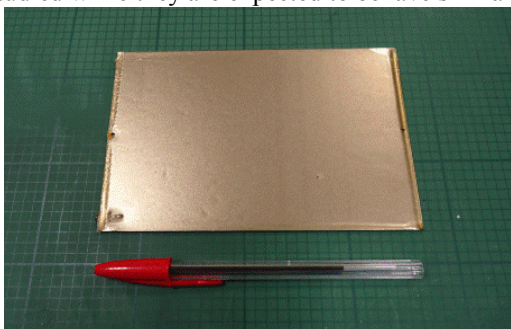


Fig. 1. Tested 90µm coated steel plate (15cm x 9cm)



Fig. 2. The experimental setup for accelerated aging tests

The factor effect calculation can be achieved by a simple matrix inversion, results are given in Table 4. Once this factors have been calculated as in any kind of regression problem, tests of hypotheses are helpful in measuring their usefulness and whether their contribution to the model are significant or no. The following section describes the analysis of variance which is carried out as test of significance.

TABLE 4: effect values for the lifespan model, vector \hat{E}

Model	Effect
M	1.45
Log(V)	-0.53
Log(F)	-0.19
Exp(-bT)	-0.54
$I_{\text{Log(V).Log(F)}}$	-0.03
$I_{\text{Log(V).exp(-bT)}}$	0.12
$I_{\text{Log(F).exp(-bT)}}$	-0.03
$I_{\text{Log(F).Log(F).exp(-bT)}}$	-0.05

Table 5 : Significance of the DoE factors effects with $k=8$ repetitions

Factor	dof	Variance	$F_{exp}=V_i/V_r$	F_{lim}	Significant?
V	1	17.0371	2218.6	4.00	Yes
F	1	2.3610	307.4	4.00	Yes
T	1	17.8524	2324.7	4.00	Yes
V,F	1	0.0209	2.7	4.00	No
V,T	1	0.3286	42.8	4.00	Yes
F,T	1	0.0169	2.2	4.00	No
V,F,T	1	0.1229	16.0	4.00	Yes
Residues	56	0.0077			

3. SIGNIFICANCE AND REPETITION NUMBER USING ANOVA

ANOVA is a widely used statistical model separating the total variability found within a data set into two components: random and systematic factors. It has been demonstrated in [10] that ANalysis Of Variance (ANOVA) is a very interesting technique to assess the statistical significance of the different factor effects in many different applications in the wide field of electrical engineering. ANOVA is now applied to the results obtained by the DoE described in section 3 in order to evaluate the significance of each effect. The normality of the distribution for each experiment is tested using a Shapiro-Wilk test and will not be described here. The independence of the different data is ensured by the fact that each test has been realized independently on different coated steel plates. DoE has been realized with 3 factors and 2 levels for each. $N=8 (=2^3)$ experiments have been set with $k=8$ repetitions for each. The results obtained applying the ANOVA on the DoE is summed up in Table 5. It confirms that voltage and temperature are the two most significant factors. Consequently, their interaction should be significant too. The effect of the frequency is significant but its interactions with other factors are not. Nevertheless, the interaction $I(V,F,T)$ is statistically significant according to ANOVA although its effect might seem low, $I(V,F)=-0.0506$. Accordingly, interaction effects between frequency and temperature, frequency and voltage, should not be taken into account in the ageing model. This method can also be used to predict how many repetitions are needed so a factor effect is significant. Full details will be given in the full paper.

4. RESPONSE SURFACE METHODOLOGY FOR MODEL IMPROVEMENT

The design of experiments can be seen as a regression method that gives to a model which can include some non-linear relationships between the stress variables. But the resulting model is limited to single factors (voltage V or temperature T for example) or products between them (VT) while some other effects such as the square of the voltage (V^2) could be influent as well and cannot be included in the first order model achieved with DoE. In these cases, Response surface methodology (RSM) is a good candidate to complete the investigations and to provide extended models [22]. In this paper, Response Surface Methodology will be used to improve previous work on lifespan modeling of the insulation of low voltage machines. A specific design is built in order to fit a second order model, which means that the experimental surface is supposed to be fitted on a particular form. The method of least squares enables to estimate the regression coefficients in this multiple linear regression model. The response estimation, η , is then given by a second order polynomial, according to (9).

$$\eta = M + \sum_{i=1}^k E_i x_i + \sum_{i=1}^k E_{ii} x_i^2 + \sum_{i=1}^{k-1} \left(\sum_{j=i+1}^k E_{ij} x_i x_j \right) \quad (9)$$

Other experiments inside the experimental domain are carried out such as the 11 points in Table 6, in order to check the validity of the different models. The same kind of model will be presented in the full paper for twisted pairs. Table 6 presents and compares the different results obtained with different models:

- DoE model has been built from 8 experiments focusing only on the main influential factors and interactions,
- SRM8 model relies on 8 experiments and includes only the most influent factors,
- SRM4 model is only based on 4 experiments randomly chosen out of the 8 experiments of SRM8 model and includes only the most influent factors.

It turns out that the use of the SRM increases the model precision and that a limited number of experiments (4 instead of 8) do not dramatically affect the corresponding model precision.

TABLE 6 : Experimental points for model verification inside the experimental domain but (not included in table 2 and 3)

	V level	F level	T level	Weibull Exp. Result (8 exp.)	DoE Model (8 exp.)	% Difference	SRM8 Model (8 exp.)	% Difference	SRM4 Model (4 exp.)	% Difference
2kV; 10 kHz; 117.5 °C	0.262	0.262	0.694	1.017	0.920	-9.5%	0.937	-7.9%	0.928	-8.4%
1kV; 5kHz; 20°C	-1	-1	-0.061	2.089	2.206	5.6%	2.137	2.3%	2.098	0.7%
2kV; 10kHz; 100°C	0.262	0.262	0.587	1.069	0.974	-8.9%	0.982	-8.1%	0.970	-9.4%
1.7 kV; 15 kHz; 26.7°C	0	1	0	1.314	1.266	-3.6%	1.321	0.5%	1.298	2.1%
1.7 kV; 8.6 kHz; 180°C	0	0	1	0.997	0.924	-7.4%	0.970	-2.7%	0.978	4.1%
3 kV; 8.7 kHz; 26.7°C	1	0	0	0.881	0.935	6.0%	0.822	-6.7%	0.785	-3.7%
2kV; 10kHz; 62.5°C	0.262	0.262	0.320	1.165	1.109	-4.9%	1.101	-5.5%	1.081	-7.4%
1.5 kV; 7.5 kHz; - 17.5°C	-0.262	-0.262	-0.481	1.771	1.915	8.1%	1.901	7.4%	1.858	5.3%
1kV; 8.6 kHz; 26.7°C	-1	-0.013	0.004	1.769	1.976	11.7%	1.833	3.6%	1.791	2.3%
1.73 kV; 5 kHz; 26.7°C	0	-1.000	0	1.704	1.642	-3.7%	1.699	-0.3%	1.675	-1.2%
1.73kV; 8.6kHz; -55°C	0	0	-1	1.986	1.993	0.4%	2.023	1.9%	1.978	-1.1%

5. CONCLUSION

This paper has improved the previous work on lifespan modeling of the insulation of low voltage machines with the help of some statistical tools such as response surface and analysis of variance. It has been shown how the most influential factors can be identified, that the SRM increases modelling accuracy and that an experiment number reduction is possible with low risks. Moreover, twisted pairs (entwined copper cords, coated by an insulator varnish) have also been studied while they are expected to behave similarly than the stator-winding insulator. The corresponding results will be included in the final paper. The objective of this work is to extend the validity domain of the model, primarily towards low constraint levels, for prognostic purposes. Other constraints such as pressure will be included in future work.

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