Lifespan modeling of low voltage machines insulation materials

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ABSTRACT. *This paper deals with the modeling of insulation material lifespan in a partial discharge regime. Accelerated aging tests are carried out to determine the lifespan of polyester-imide insulation films under different various stress conditions. The insulation lifespan logarithm is modeled as a function of different factors: the electrical and frequency stress logarithms and an exponential form of the temperature. The model parameters are estimated on a training set. The significance of the factors is evaluated through the analysis of variance (ANOVA). In a first step, the design of experiments method (DoE) is considered. The associated lifespan model is linear with respect to the factors. This method is well known for reducing the number of experiments while providing a good accuracy. In a second step, the response surface method (RSM) is considered. This method takes also into account some second order terms and thus possible interactions between the stress factors. Performance of the two methods are analyzed and compared on a test set.*

RÉSUMÉ. *Ce travail traite de la modélisation de la durée de vie de matériaux d'isolation sous régime de décharges partielles. Des tests de vieillissement accélérés sont réalisés pour déterminer la durée de vie des films isolants polyester-imide dans différentes conditions de stress. Le logarithme de la durée de vie est modélisé comme une fonction de plusieurs facteurs : les logarithmes de la contrainte électrique et de la fréquence et une forme exponentielle de la température. Les paramètres du modèle sont estimés sur un ensemble d'essais. L'importance des facteurs est évaluée par l'analyse de la variance (ANOVA). Dans une première étape, la méthode des plans d'expériences est considérée. Le modèle de durée de vie associé est linéaire par rapport aux facteurs. Cette méthode est bien connue pour réduire le nombre d'expériences tout en assurant une bonne précision. Dans une seconde étape, la méthode de surface de réponse est considérée. Cette méthode tient également* *compte de certains termes de second ordre et les interactions ainsi possibles entre les facteurs de stress. Les performances des deux méthodes sont analysées et comparées sur un ensemble de tests.*

KEYWORDS: *electrical insulation, accelerated aging, lifespan estimation, modeling, response surface, analysis of variance, films, twisted pairs.*

MOTS-CLÉS: *isolation électrique, vieillissement accéléré, estimation de la durée de vie, modélisation, surface de réponse, analyse de la variance, films, paires torsadées.*

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1. Introduction

Low voltage electric machines are increasingly submitted to heavy electric constraints and their lifespan becomes nowadays a great concern. Among many papers, Tavner (2008) has reported that stator-winding insulation is one of the weakest components in a drive (around 40% of failures). Many operating factors such as voltage, frequency, temperature, pressure, etc. could have a dramatic effect, all the more that these stresses can interact between each other as shown in Yang et al (2007). 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 to the aging mechanism. As examples, Mazzanti (2009) and Crine (2005) include the physical, thermal and electro-mechanical aspects of the electrical aging process. Additionally, the choice of the lifespan model as a function of these factors remains critical. Various models can be found in the literature (see Bartnikas and Morin (2004) for instance). Most models 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, especially with Pulse Width Modulation (PWM) supply.

Experimental tests are required to assess lifespan modeling. However, full aging tests performed under nominal conditions and taking into account all the factors involved in the aging process, are of prohibitive cost. As a consequence, accelerated aging tests, which aim at speeding up the degradation, are generally performed. The objective is to predict the lifespan under nominal conditions from a model estimation in extreme conditions. The “Design of Experiments” (DoE) method (Fisher, 1935) has been successfully used either for experiment optimization or modeling purposes. In the original method, a set of eight experiments is carried out for each combination of the stress factors (voltage, temperature and frequency). To be even more cost effective, this paper reduces the number of experiments. An Analysis of Variance (ANOVA) is then conducted to check the resulting model estimate validity.

Section 2 describes the studied materials and test bench and the state of the art DoE method. Section 3 presents factor significance analysis using ANOVA. Section

4 proposes response surface method for model improvement. Section 5 extends the study to the lifespan modelling of enamelled PEI-PAI wires. Conclusions and future works are discussed in section 6.

2. System description and state-of-the-art DoE method

The test bench itself and the tested insulation materials have been fully described in Lahoud *et al.* (2013). The tested insulation materials consist of steel plates coated with polyester-imide films (PEI - thermal class: 180°C) that 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 and are by far cheaper.

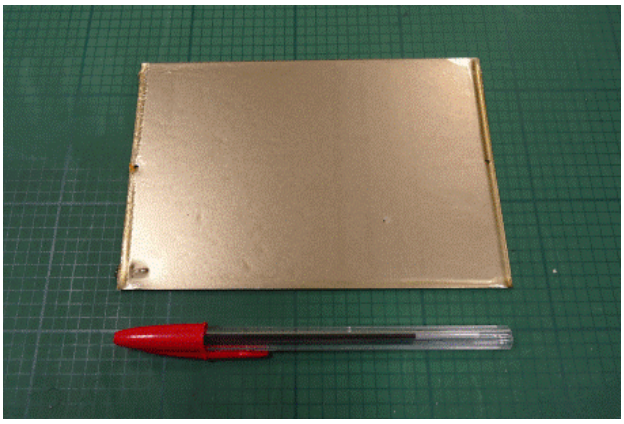

Figure 1. Tested 90µm coated steel plate (15cm x 9cm)

Accelerated Life Testing (ALT) is carried out, *i.e.* materials are submitted to extreme constraints to test their degradation without waiting until normal failure. The use of inverted-fed rotating machines enhances over-voltages and non-homogeneous voltages in the wiring. These heavy conditions can reach twice the nominal voltage just after the voltage application. Voltage and frequency are the main causes of the apparition of partial discharge (PD) into the isolator. PD can be defined as a localized dielectric breakdown of a small portion of a solid or fluid electrical insulation under high voltage stress. The discharge is said partial since it does not bridge the space between two conductors. In addition, several other factors can affect the insulation degradation such as temperature, depression, humidity, chemical or mechanical stresses. Furthermore, cycling some of these stresses can also impact the lifespan! Cycling can thus be considered as another degradation factor (Kokko, 2012; Bertsche, 2008).

Figure 2. The experimental setup for accelerated tests

The aging process is driven by several stresses acting simultaneously such as electrical, thermal, mechanical and ambient stresses. A review of the existing literature highlights four major factors affecting the lifespan: voltage amplitude (V) and frequency (F) of the supply periodic square waves, temperature (T) and temperature cycling. For simplicity and as a first modeling attempt, only the first three stresses are studied. Their extreme values are such that the insulation degradation is principally due to PD.

Eight samples were tested in our experimental setup, shown in Figure 2. Under electrical stress, the steel plate acts as the first electrode and a spherical stainless steel electrode (diameter: 1mm) is the second. Samples were placed in a climatic chamber where the temperature is fully controlled. The lifespan of each sample was measured using a timer (one per sample) which stopped counting as soon as the measured current exceeded a predefined threshold corresponding to the sample break down. The faulty specimen was disconnected while the survivors remained under voltage and at the controlled temperature. Accelerated aging tests are carried out in order to relate the applied external stresses (factors) to the insulation lifespan (response). Lifespan data in this paper is presented according to the Weibull statistical distribution (Bertsche, 2008). This distribution is commonly used for lifespan modeling. However, for simplicity and because of their influence, only three major parameters were studied:

– the square wave applied HVDC (*V*),

– the frequency of the applied voltage (*F*),

– temperature (*T*).

Their extreme and average values (the so-called levels of the considered modeling methods) are given in Table 1. According to Lahoud *et al.* (2013), in the case of PEI material under PD regime, the insulation lifespan logarithm follows an inverse power model depending on *log(V)*, *log(F)* and *exp(-bT)*. Constant $b=5.64\text{x}10^{-3}$ derives from calculations detailed in Lahoud *et al.* (2013) from lifespan experimental results with respect to the temperature (for V=2kV and F=10 kHz *i.e.* at the center of the experimental domain).

Table 1. Levels of the three stress factors

Factors	Level (-1)	Level (+1)	Level (0)
Log (Voltage (kV))	1	3	1.73
Log((Frequency (kHz))	5	15	8.7
Exp(-b.Temperature (°C))	-55	180b	26.7b

with $b = 5.64\text{x}10^{-3}$

Table 2. Experimental results with 3 factors at 2 levels each: 8 experiments with 8 film samples each

	Log (V)	**Log (F)**	$\mathbf{e^{(-bT)}}$	**Lifespan (minutes) n° Sample**							
Test n°	**F1**	**F2**	**F3**	**no. 1**	**no. 2**	**no. 3**	**no. 4**	**no. 5**	**no. 6**	**no. 7**	**no. 8**
1	-1	-1	-1	378	418	568	587	634	642	786	850
2	-1	-1	1	25	29	23	29	26	30	24	31
3	-1	1	-1	169	187	268	268	343	364	162	322
4	-1	1	1	14.5	14.25	13.4	13.8	14.8	15	13	15.5
5	1	-1	-1	26	30	28	33	24	29	28	35
6	1	-1	1	6	6,5	6,2	6,8	5,5	6,5	6	6.3
7	1	1	-1	14	16.21	15.07	15.5	15.28	16	12.5	14.8
8	1	1	1	2.2	2.233	1.133	1.65	2.033	1.516	0.933	1.4

The first considered method for the PEI film lifespan modeling is the DoE method (Lahoud *et al.*, 2011; 2013). The associated experimental plans and corresponding results are given in Tables 2 and 3 for an easy understanding. Table 2 gives the 2^3 (3 factors, 2 levels each) possible combinations between the different factor levels. Note that the $N=8$ experiments have been performed with $k=8$ repetitions for each. Table 3 lists the associated measured lifespans (in minutes). The method models the lifespan logarithm as a function of the logarithms of the electrical stress (*i.e.* voltage and frequency) and an exponential form of the temperature as expressed in (1). The estimated model coefficients are listed in Table 4 for films but the same kind of model holds for twisted pairs.

Table 3. Full factorial design matrix for three factors (V, F, T) with 2 levels each, 8 films samples

Test n°	Log(V)		Log(F)	$e^{(-bT)}$	Log(V).Log(F)	Log(V). $e^{(-bT)}$	Log(F). $e^{(-bT)}$	Log(V).Log(F) .$e^{(-bT)}$	Log(L)
	M	**F1**	**F2**	**F3**	**I(V.F)**	**I(V.T)**	**I(F.T)**	**I(V.F.T)**	**Weibull**
1	1	-1	-1	-1	1	1	1	-1	2.824
2	1	-1	-1	1	1	-1	-1	1	1.453
3	1	-1	1	-1	-1	1	-1	1	2.459
4	1	-1	1	1	-1	-1	1	-1	1.167
5	1	1	-1	-1	-1	-1	1	1	1.486
6	1	1	-1	1	-1	1	-1	-1	0.806
7	1	1	1	-1	1	-1	-1	-1	1.187
8	1	1	1	1	1	1	1	1	0.255
Tests at the center of the study domain									
Model : Log(L)=f[Log(V), Log(F) and exp(-b.T)]									
9	1	0	0	0	0	0	0	0	1.43

$$\mathrm{Log}(L) \sim M + E_V.\log(V) + E_F.\log(F) + E_T.\exp(-bT) + E_{FV}.\log(V).\log(F) + E_{VT}.\log(V).\exp(-bT) + E_{FT}.\log(F).\exp(-bT) + E_{VFT}.\log(V).\log(F).\exp(-bT) \quad (1)$$

The factor effects are derived using a simple matrix inversion. The corresponding results are given in Table 4 and Figure 3. Once these factors have been derived, it is possible to evaluate their contribution to the model. The following section describes the ANOVA which is carried out to test the factor significance.

Table 4. Factor effect values

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

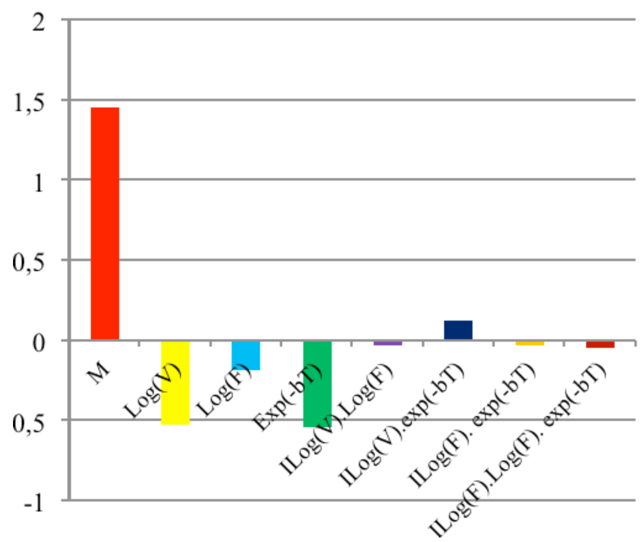

Figure 3. Bar-graph representation of the factor effects

3. Factor significance analysis using ANOVA

ANOVA is a widely used statistical method used to separate the total variability found within a data set into a random and a systematic contribution. It has been demonstrated in Bertsch (2008) that ANOVA is helpful in assessing the statistical significance of the different factor effects in many different applications, and in our concern in the field of electrical engineering. ANOVA is applied to the DoE results described in Section 2 in order to evaluate the significance of each factor. 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 measurements 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 to the DoE is summed up in Table 5. It confirms that voltage and temperature are the two most significant factors. Consequently, their interaction is also significant. 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.

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	17.037	2218	4.00	Yes
F	1	2.3610	307	4.00	Yes
T	1	17.85	2324	4.00	Yes
V,F	1	0.021	2.7	4.00	No
V,T	1	0.329	42.8	4.00	Yes
F,T	1	0.017	2.2	4.00	No
V,F,T	1	0.123	16.0	4.00	Yes
Residues	56	0.0077			

4. Response surface method for model improvement

The DoE method is a regression method providing a model that can include some non-linear relationships between the stress variables. However, the resulting model only takes into account the factors (voltage V or temperature T for example) independently or products between them (VT). Some other effects such as the square of the voltage (V^2) could be influent as well and cannot be included in the DoE model. Response surface method (RSM) is a good candidate to complete the investigations and to provide extended models (Myers and Montgomery, 2002).

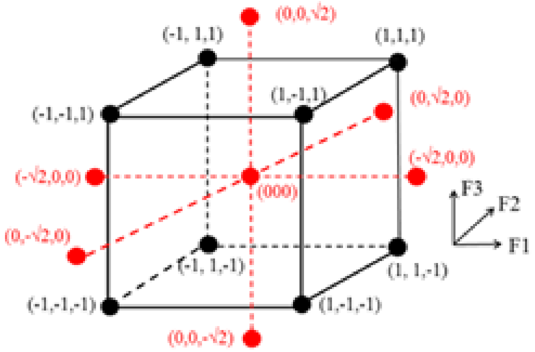

Figure 4. Graphic representation of the experimental points in a DoE (black) and in a CCD (in red)

As in DoE, RSM organizes the experiments, minimizes their number and maximizes model accuracy. However, some central experiments (all levels equal to 0 when considering centered reduced variables) must be also tested to ensure certain properties. Consequently, the RSM design will have at least 3 levels, increasing the number of levels compared to DoE. Fortunately, experiments used in DoE can be reused in RSM.

The most popular design of RSM is the Central Composite Design (CCD) which considers an extra level α for several factors. The value of α is chosen to guarantee particular properties, such as listed in Myers and Montgomery (2002). In this paper, to ensure the orthogonality property (with a number of 4 experiments in the center of the experimental domain), α must be equal to $\sqrt{2}$ as displayed in Figure 4. Consequently, 5 levels [$-\sqrt{2}$; -1; 0; +1; $+\sqrt{2}$] are chosen for each factor. The effect vector E can be computed like in the DoE method using expression (2):

$$\hat{E} = \left(X^t \cdot X\right)^{-1} \cdot X^t \cdot Y \tag{2}$$

In this paper, RSM is also used to improve lifespan modeling of the insulation of low voltage machines (films and enameled wires). A specific design is built in order to fit a second order model, (including the effect of V^2 for ex.), 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 (3):

$$\eta = M + \sum_{i=1}^{k} E_i . x_i + \sum_{i=1}^{k} E_{ii} . x_i^2 + \sum_{i=1}^{k-1} \left(\sum_{j=i+1}^{k} E_{ij} . x_i . x_j \right) \tag{3}$$

Additional experiments inside the experimental domain are carried out in order to check the validity of the different models. Table 6 presents and compares the results obtained with different film lifespan models:

– DoE model has been built from 8 experiments focusing only on the main influential factors and interactions,

– RSM8 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 RSM8 model and includes only the most influent factors.

It turns out in Table 6 that the use of the RSM significantly increases the model precision and that a reduction of the sample number (4 instead of 8) does not dramatically affect the model accuracy.

Table 6. Experimental points for film lifespan model verification inside the experimental domain but (not included in Tables 2 and 3)

	V level	F level	T level	Weibull Exp. Result (8 samples)	DoE Model (8 samples)	% Diffe-rence	SRM8 Model (8 samples)	% Diffe-rence	SRM4 Model (4 samples)	% Diffe-rence
2kV; 10kHz; 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; 8.6kHz; 180°C	0	0	1	0.997	0.924	-7.4	0.970	-2.7	0.978	4.1%
3 kV; 8.7kHz; 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; 7.5kHz; -17.5°C	-0.262	-0.262	-0.481	1.771	1.915	8.1	1.901	7.4	1.858	5.3%
1kV; 8.6kHz; 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; 5kHz; 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. Modeling lifespan of wire

5.1. *Models with DoE and RSM*

This work also estimates the lifespan of motor wirings. In order to establish a lifespan model of the rotating electrical machine wiring insulation, the tested materials are twisted pairs covered with a double varnish of Poly-Ether-Imide (PEI) and Poly-Amide-Imide (PAI) with a thermal class of 200°C (Ederfil C200 with a diameter of 0,5mm), as shown in Figure 5. Twisted pairs are manufactured according to the American National Standard (ANSI/NEMA MW 1000-2003, Revision 3, 2007). The varnish provides electrical insulation all along the surface without significantly increasing the volume or the weight. Electrical insulator varnish degrades across time and when submitted to electrical constraints. The insulator is designed to last for several thousand hours, but if the nominal constraints are over-passed the lifespan decreases dramatically.

It is well known that PD appear into the insulation of rotating machines fed by inverters (Ortega and Castelli-Dezza, 2010; Guastavino *et al.*, 2011). PD can be defined as a localized dielectric breakdown of a small portion of a solid or fluid electrical insulation under high voltage stress. The discharge is said partial since it does not bridge the space between two conductors. The insulation varnish is the first element in contact with PD and the most affected part of the insulation.

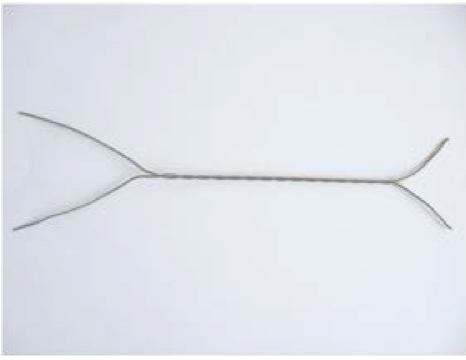

Figure 5. Enameled wire PEI-PAI thermal class: 200°C

This study compares the models obtained with DoE, RSM and MLR. The experiments have been chosen in order to be used in the three methods. Experiments are organized as explained in the Table 7, where 30 experiments have been carried out. Some of them are used to estimate the wire lifespan model parameters whereas the others are used to test the model validity.

Table 7. Number of experiments vs identification method

DoE	8 exp.
RSM	8 from DoE + 6exp. + 4CP
Extra experiments	12 exp.

Thanks to DoE, the wire lifespan model M1 can be expressed as follows in (4) and (5):

$$\begin{aligned} & Log(L) \approx M + E_V \cdot Log(10V) + E_F \cdot Log(F) \\ & + E_T \cdot Exp(-b \cdot T) + I_{VF} \cdot Log(10V) \cdot Log(F) \\ & + I_{VT} \cdot Log(10V) \cdot Exp(-b \cdot T) + \\ & I_{FT} \cdot Log(F) \cdot Exp(-b \times T) + \\ & I_{VFT} \cdot Log(10V) \cdot Log(F) \cdot Exp(-b \cdot T) \end{aligned} \tag{4}$$

$$\begin{aligned} & Log(L) \approx M + \sum E_i \cdot x_i + \sum I_{ij} \cdot x_i \cdot x_j \\ & + \sum I_{ijk} \cdot x_i \cdot x_j \cdot x_k \end{aligned} \tag{5}$$

However, this model, estimated from 8 experiments only with DoE, when applied on twisted pairs, does not provide a very accurate lifespan prediction of the experiments composing the test set. The maximum error, derived from the test set and given in Table 8, is far too high.

Table 8. Relative errors between wire lifespan model M1 and the 12 extra experiments (long and short lifespan)

Average error	63%
Max. error	281.5%
Min. error	0.01%

In the case of RSM, the lifespan model M2 is the same as for DoE but with 3 extra squared terms (6).

$$\begin{aligned} & Log(L) \approx Model_{DoE} + I_{VV} \cdot Log^2(10V) \\ & + I_{FF} \cdot Log^2(F) + I_{TT} \cdot Exp(-2b \cdot T) \end{aligned} \tag{6}$$

In this case also, the model parameters (estimated from the 8 DoE experiments plus the 10 additional experiments needed for RSM) cannot be validated on the test set, as seen in Table 9 because of too large errors. The effects of the stress factors can be read in Figure 6, where several criteria are listed: average lifespan, median lifespan which could exclude outliers and average Weibull lifespan. The last form based on the Weibull distribution was finally chosen due to its wide use. Figure 6 points out the most influential contributions on lifespan model *i.e.* Voltage, temperature and their interactions.

Obviously, mean errors are a little bit lower than for DoE but it is more important to notice that there is an aberrant lifespan with an absolute error of

483.1%. Once removed, the mean error decreases down to 37.5% and the max error to 150%. However, these results do not validate the lifespan model of the twisted pairs. In addition, studying the errors reveals that the biggest errors are always for very short lifespan. This fact seems to indicate a different degradation regime for short lifespan leading to a different model.

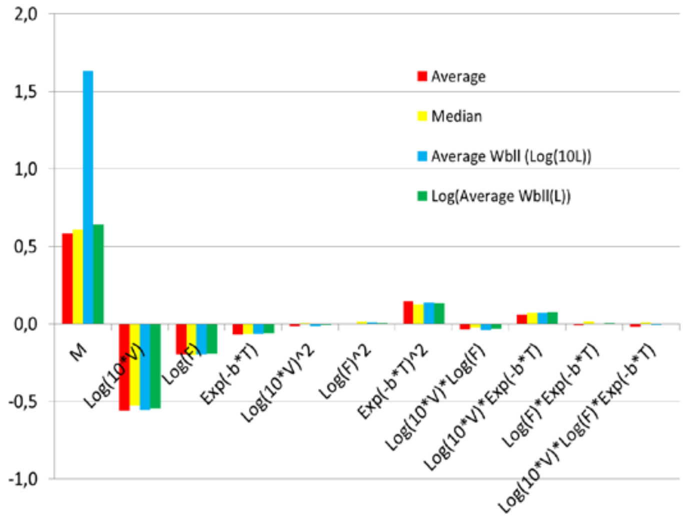

Figure 6. Average effects of the stress factors with DoE and SRM on wire lifespans

Table 9. Relative errors between wire lifespan model M2 (SRM) and the 12 extra experiments (long and short lifespan)

Average error	51.4%
Max. error	483.1%
Min. error	0.8%

5.2. Models with Multiple Linear Regression (MLR)

DoE or RSM can be seen as regression methods taking into account nonlinear relationships between the stress variables. More generally, classical regression methods do not include any consideration on the experiment organization. The most common regression method is the linear regression. Nevertheless, as a multi-stress modeling problem is treated, simple linear regression cannot be used. The regression method that fits this problem is the multiple linear regression method (MLR) (Weisberg, 2005). MLR performs the derivation of the least square estimator of the factor effects as follows in (7).

$$\hat{E} = \left(X^t \cdot X\right)^{-1} \cdot X^t \cdot Y \tag{7}$$

Calculations are similar to those of DoE or RSM but, in this case, the elements of matrix X are not normalized levels but the real value of each factor. Moreover, there is *a priori* no constraints for the choice of these experimental points. Multiple Linear Regression (MLR) will be the last studied method. First of all, in an attempt to compare the different methodologies, the model of Equation (8) is first estimated from 11 randomly chosen experiments leading to the so-called model M3.

$$Y \approx \sum_{i=0}^{10} \hat{\beta}_i \cdot x_i \tag{8}$$

The β_i 's are the model parameters and the x_i 's are the real values of the so-called explanatory variables M, *Log(10V)*, *Log(F)*, *Exp(-bT)*, *Log²(10V)*, etc. in the same order than in the RSM model. As previously, lifespan depends on the factors and on their interactions. For comparison purpose, the same type of model is used than for the RSM. However, in the case of MLR, different expressions could have been chosen. The results show that the mean error is similar to those of RSM (38%) in Table 10. For performance improvement, the experiments corresponding to very short lifespan (less than 1.5 minutes) are removed and the number of experiments is increased. Indeed, small lifespan can be seen as outliers in the need for long lifespan models. Moreover, the MLR imposes no constraint on the experiment number and distribution, thus they can be chosen in particular ranges of interest. Estimation with 16 experiments and without the shortest lifespan generates a better model (M4) than before. From now on, all the errors in Table 11 remain lower than 55%.

Table 10. Relative errors between wire lifespan model M3 (MLR11) and the other experiments

Average error	38.1%
Max. error	150.4%
Min. error	0%

Consequently, it can be assumed that the very short lifespan do not follow the same model as long lifespan: a single model with a reasonable number of parameters is not sufficient to represent at the same time short and long lifespan. Thus, experiments corresponding to short lifespan must be removed for an accurate modeling of long lifespan. To check this hypothesis, lifespan lower than 3 minutes are also removed. The model is now estimated with 13 experiments only and tested on 6 experiments as in Table 12. In this case, the model estimation is particularly accurate.

Table 11. Relative errors between wire lifespan model M4 (MLR16 without very the short lifespans) and the other experiments

Average error (Lifespan>1,5 min)	12.4%
Max. error	55%
Min. error	0.3%

Table 12. Relative errors between wire lifespan model M4 (MLR16 without very the short lifespans) and the other long lifespan experiments

Average error	5.3%
Max. error	29.7%
Min. error	0.1%

6. Conclusion

This paper extended our previous work on lifespan modeling of the insulation of low voltage machines with the help of some statistical tools such as RSM and ANOVA. The most influential factors have been identified. It has been shown that the RSM increases the modeling 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 analysis of the estimation performance on an appropriate test set has shown that the same model cannot simultaneously fit very short and long lifespan. It might be assumed that short lifespan (under 3 minutes) are due to phenomena that are not taken into account in the proposed models. Moreover, lifespan in twisted pairs are much shorter than in the steel plates insulated with PEI. Consequently, factor values must be chosen to avoid very short lifespan.

The ability of the DoE and the RSM to organize and to limit the number of experiments is confirmed. However, the models derived using these methods cannot benefit from additional randomly chosen experiments. From this point of view, MLR shows more flexibility. After a first analysis with the two first methods, regression can help to analyze different regions inside the studied domain and to eliminate outliers that might be due to defaults in materials or in the test bench.

Our objective 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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