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Lifespan and Aging Modeling Methods for Insulation Systems in Electrical Machines: a Survey

P. Maussion, IEEE Member, A. Picot, IEEE Member, M. Chabert and D. Malec

***Abstract*-- This paper deals primarily with modeling lifespan and, to a lesser degree, aging in insulation systems of electrical machines. The different aging processes involved, including partial discharges, are described. Previous works, in conjunction with the current study, are described and lead to the conclusion that there is no single method, even with accelerated lifetime tests, able to provide lifetime models taking into account all the stress factors in a simple way. Consequently, the principles of different regression methods are described (design of experiments, response surface, multi-linear and robust regression) and applied with a limited number of experiments, thus reducing experimental cost. Several types of insulation material were tested in order to confidently recommend one in particular.**

***Index Terms*-- AC machines, Aging, Accelerated Aging, Condition monitoring, Design of Experiments, Electric machines, Insulation testing, Lifetime estimation, Modelling, Pulse width modulated inverters.**

I. Nomenclature

E_i	Effect of factor number i
E_{ij}	Effect of interaction between factor i and j
y_i	Experimental value at experiment number i
F_i	Normalized level of factor i, could be +1, -1 or any value between -1 and +1
M	Average experimental value
L	Lifespan in minutes
T	Temperature in °C
V	Voltage in V
F	Frequency in Hz
n	Number of experiments
N	Number of samples = number of repetitions

II. Introduction

The monitoring of stator insulation is becoming more and more widespread both in high-voltage and low-voltage machines. It is particularly important as it helps to improve the reliability of systems. It can save time and money by avoiding unplanned maintenance and extending lifespan. It improves safety for staff, public and equipment, by decreasing the risk of accidents or fire. Any number of stresses can cause the premature failure of a component in electrical machines: thermal, mechanical, electrical and environmental stresses and it is important to narrow down the most likely causes of failure. Few papers deal with condition monitoring of electrical machines such as [1] where an extensive review of motor failure is extracted from the literature. Notably, faults in low-voltage induction machines are mainly bearings faults. But the rising proportion of electric energy in embedded systems means an increase in the dc bus voltage. As a consequence, stator windings could be the place for partial discharges (PD), even in low-voltage machines and especially for random-wound stators.

PD off-line and on-line detection has been extensively described in [2] for low voltage machines and in [3] for high-voltage machines, particularly in the petrochemical industry. PD detection, with a pioneer work in [4], is currently being carried out thanks to high-frequency measurement and acquisition devices (up to Ghz) and wideband frequency response sensors. Nevertheless, the resulting damage evaluation and the corresponding remaining life expectancy remains an issue. Some PD aging or lifetime models will be presented in the following sections. For the past few years, the objectives of our work have been to provide useful guidelines for experimental insulation lifespan modeling with Accelerated Lifetime Tests (ALT), whatever the degradation phenomenon involved, with or without PD. Once a model is obtained, our final aim is to derive the actual lifetime for prognosis. This paper is organized as follows: Part III presents partial discharges, part IV provides a comprehensive presentation of Accelerated Lifetime Tests in electrical engineering and their use for PD characterization. Principles of different regression methods are recalled in part V. Part VI focuses on our test benches and part VII on our results through models and their validation tests.

III. Partial Discharges

The number of low voltage motors fed by inverters has greatly increased since the mid80's when these inverters became both more efficient and cheaper. New stresses have emerged related to high dV/dt inverters (typically higher than 1kV/µs), such as surge voltages occurring either at the motor terminals or in the motor windings.

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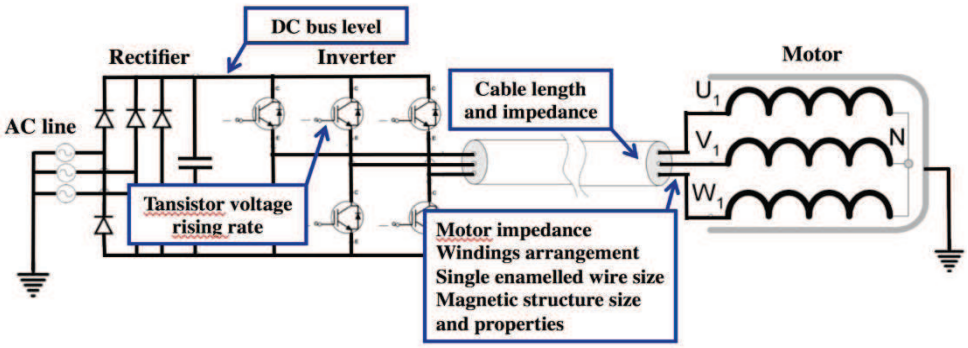

Fig . 1. Typical parameters influencing the electrical stress in a motor winding fed by an inverter

The over-voltage occurring at the motor terminals might be due to an impedance mismatch between the feeding cable and the windings to the rise in the high voltage rate of the inverter switches. This over-voltage can theoretically reach $2U_{bus}$, i.e. more than 1kV when using a 540V DC bus. If the motor works in a regenerative brake mode, the DC bus voltage increases and the corresponding over-voltage at the motor terminals can be consequently higher than $2U_b$.

An over-voltage also occurs within the windings themselves. As the voltage propagation is not instantaneous in the winding (speed is inversely proportional to the square root of the product LC where L and C are the linear inductance and capacitance of the winding), the voltage distribution in the windings is far from homogeneous. In other words, during the first 100ns or first µs (depending on the size of the stator) following the voltage application, the first turns are electrically energized but not the last ones.

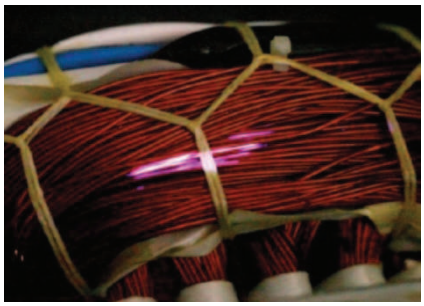

Fig. 2. Typical PD between neighbouring turns in a PWM fed motor[2]

Consequently, over-voltages are induced in the winding, especially in the first turns of form-wound motors. In the case of a random-wound stator in which each turn could be placed randomly against any other turn of the coil, this over-voltage may take place between phase/phase and winding/ground insulations (enamel, varnish, ground insulation films, etc.). The electric stress at both motor terminals and within the windings depends on different factors which are summarized in Fig. 1. This problem is related to air, either in the embedded or open voids existing in the insulation system, which, when these over-voltages take place, can be exposed to voltages sufficiently high to initiate a PD activity (i.e. higher than the Paschen's values [5]). An example of a PD phenomenon occurring in the stator fed by a PWM (Pulse Width Modulation) inverter [4] and a resulting breakdown between turns are given in Fig. 2. The effects of these discharges are:

- delamination, erosion, etc. because of the ion-induced surface degradation,
- increase in the local temperature which may reach the melting point of the insulator,
- increase of the chemical degradation of the insulator by creating aggressive substances like nitric acid, ozone, etc.
- transformation into a total discharge (arc) when the insulator is completely destroyed by the PD.

Unfortunately, classical Electrical Insulation Systems (EIS) of such low voltage motors (Polyether, Polyetherimide, Polyamide-imide, Polyimide, Polyethylene terephthalate, Epoxide, etc.) are not able to support such PD activity and their lifetime is significantly reduced. In the 'more electrical aircrafts', numerous motors will be supplied by PWM converters, it is therefore necessary to study the reliability of such motors, taking into account their extreme environmental working conditions. As a consequence, PD may be induced within the EIS in existing air gaps [6] or defects which appear with aging [7]:

- low pressure in non-pressurized areas which leads to low partial discharge inception voltages (PDIV),
- thermal cycles able to create delamination in the EIS which may initiate PD,
- humidity cycles able to modify the PD activity and bring pollution into the EIS.

For all these reasons, extensively listed in numerous papers, PD is an issue of great scientific and industrial importance, but very difficult to tackle. [8] pinpoints that the correct interpretation of PD tests can only be performed if periodic measurements are achieved. Several conditions must be fulfilled regarding the uniformity of test conditions such as temperature, humidity, load level, supply voltage, test instrument and measurement procedure. Any change between two results will certainly lead to misinterpretation. The following section presents off-line tests, where stress parameters are controlled in order to derive reliable conclusion.

IV. ACCELERATED LIFETIME TESTS

A. ALT principles and applications

Accelerated Lifetime Tests (ALTs) are commonly used in testing procedures, in product design and for evaluating the reliability of components, devices or systems. Units are tested at higher than usual levels of stress, such as temperature, voltage, current, pressure, frequency, etc. depending on the device under test. Stress levels must remain lower than maximum values in order to avoid irrelevant degradation mechanisms. ALTs accelerate the degradation phenomena, save time and money, especially when the expected lifespan of the components is in the range of years. The testing conditions should lead to the same degradation phenomena as during normal service and that the models obtained must fit to experimental data. Otherwise, some acceleration factors should be included in the aging models.

In recent literature, ALT for electronic engineering have been applied to the estimation of lifetime models for Lithium-ion battery cells or $LiFePO_4/C$ battery system for wind power applications to estimate the correlation of electrical and mechanical properties of LV nuclear power plant cables, to compare different power cycling strategies to test power devices. Accelerated aging procedures are described in [9] for assessing correlations between electrical and mechanical properties of LV power plant cables in the very specific domain of nuclear power. In that case, stress factors are the temperature and gamma radiation levels and degradations are evaluated through different lab tests such as dielectric spectroscopy, tensile testing and density measurements. One conclusion of this paper is that sequential aging (different stresses one after the other) could be inefficient for the purpose of simulating the ageing of service insulation. On the contrary, it was found that simultaneous aging has significant effects on material properties.

As LEDs are gradually taking over as preferred lighting systems, their lifespan is also of the utmost importance, particularly for economic reasons. In [10], three different life models are derived from ALT under step-varying forward current (with load cycles), considered here as the most influential stress factor. This work compares the effects of constant and non-constant current stress applied to 8 LEDs at once. Similarly to our work which is described below, the errors between model predictions and experiments are reduced for large lifespans.

Of course, battery lifetime is a very important issue, both for embedded systems such as electric vehicles and for stationary energy storage in some wind power plants for example. Battery energy storage systems can provide promising solutions for smoothing the power produced by wind power plants and by extension, for any fluctuating renewable energy source. Recent papers tackle the lifetime estimation through modeling after accelerated tests. Li-ion batteries are tested in [11] under different stress conditions (temperature, depth of discharge (DOD) cycle and state-of-charge (SOC). These three factors have three levels each leading to $3^3 = 27$ possible cases which all had to be tested for a reduced set of three battery cells in a serial connection. However, in order to reduce the experimental cost, all the experiments were carried out at an average SOC level of 50%, consequently only 9 experiments were necessary but the validity of the model is thereby reduced. Finally, the derived models are only two-dimensional as time and temperature are involved. Model coefficients are obtained by a classical curve fitting method and model validity are tested under specific mission profiles with very good agreement.

Indeed, very few papers deal with insulation system lifespan modeling and/or the tests required for this. Nevertheless, with the increasing electrical power in embedded systems for various applications such as energy generation, traction, air conditioning, etc., the challenges of partial discharge detection or withstanding is of paramount importance.

B. PD and ALT

For inverter-fed rotating machines, the International Standard Commission (IEC) published specific standards [12] and [13], respectively considering type I machines, supposed to operate without any partial discharge and type II that can cope with moderate levels of PD. Type II are defined in [14], as "*insulation system of stator/rotor windings of single or polyphase AC machines which are subjected to repetitive impulse voltages, such as pulse width modulation (PWM) converters and expected to withstand partial discharge activity during service*". Additionally, [14] upgrades IEC 60034-18-41, from a technical specification to a standard, with a new value: Impulse Rated Voltage (IRV); this value will be printed on the machine plate. These documents describe the required tests to qualify a material with regard to this norm, with several test voltages chosen so as to produce mean times to failure in the range from 100h to 3000h. [13] provides lifetime formulas between voltage and frequency in steady state. Despite its well-documented influence, temperature is not taken into account. Combining the frequency and voltage- dependent aging formulae leads to the general expression (1) which can easily be plotted as lines in a Log-Log representation.

$$L_{f2,u2} = L_{f1,u1} \cdot \left(\frac{U_1}{U_2}\right)^n \cdot \left(\frac{f_1}{f_2}\right) \qquad (1)$$

L_{f2u2} is the lifetime at frequency f_2 and voltage U_2, respectively with f_1 and U_1 and n is the voltage endurance coefficient, i.e. the slope of the graph of log (applied voltage) vs log (time to failure) at 50/60 Hz. This model form with L as a power of V and F was chosen in section VI of this paper.

The characteristics of the test signals are important as described in [16]. Sinusoidal and square waveform supplies are compared in terms of PD generation in MV machines. In these experiments, 5 enameled twisted pairs with a single contact point are tested under 3.5kV with different

waveforms, different frequencies and different rise times. PD is recorded with a ultra-high frequency test bench to explain their influence on insulation endurance. An original and interesting analysis compares the different test signals not only with respect to lifespan (in minutes) but also by counting the number of pulses to breakdown, i.e. taking into account the signal frequency. Surprisingly, low frequency test signals induce a higher degradation due to PD. Besides, [16] shows that PD intensity in low-voltage and medium-voltage inverter-fed machines is not directly related to frequency, even with impulsive voltage test signals, but that rise time has much more influence. Aging or lifespan tests have to be designed accordingly and in order to adapt to in-service conditions.

Regarding temperature, [17] specifies the general ageing conditions and procedures to be used for deriving thermal endurance characteristics and provides help in using the detailed instructions and guidelines in the other parts of the standard [18]. This part of IEC 60216 gives guidance on the choice of the test criteria for the determination of thermal endurance characteristics. It includes a list of existing published procedures which is non-exhaustive. This model form for Log (L) as an inverse power of T was chosen section V of this paper.

Finally, it is important to notice that population size is an issue. In [19] particularly, the effect of "small" sample size is investigated. However 80 units is still significantly more than in real-life conditions for stator insulation aging effects and PD.Turn-to-turn isolation is monitored in [20] [21] through the off-line measure of the variation in the winding turn-to-turn capacitance and of the Partial Discharge Inception Voltage (PDIV). Different twisted enameled wire pairs are tested along 10 thermal cycles lasting 24 hours at 280°C, according to the standard EN 60172. Turn-to-turn capacitance and PDIV measurements are performed before and after each thermal aging cycle. There is an obvious correlation between an increased capacitance and a reduction of the PDIV between aging cycles. This could lead to a new health indicator provided that a reliable and easy to obtain link is found between the two quantities.

Based on the same principle that winding capacitor variations should be in relationship with degradation, [22] [23] suggest monitoring machine health by evaluating its high frequency properties. Additional capacitors are put in parallel with the machine windings in order to emulate insulation degradation. The measurement method involves a voltage step excitation of the machine by the switching of the inverter. Insulation health indicator of the three phases of the machine is derived after signal processing of the phase currents even with current sensor bandwidths limited to hundreds of Khz and with only two phase current sensors. Experimental validation tests are achieved on two test machines (5.5kW and 1.4MW) with different insulation systems. The influence of moisture is evaluated as negligible and the authors recommend using the same temperature throughout the test as it may influence the results.

V. Regression methods for lifespan modeling

A. General considerations

Lifespan modeling is a complex task due to the large number of phenomena and factors involved. Developing a lifespan model based on physics is not an easy task and often focuses on a single factor. Different expressions have been proposed in the literature such as the Arrhenius law [24] for one factor or the Eyring model [25] in the case of multiple factors. Empirical and physical models have been developed to relate the insulation aging mechanism or lifespan with applied stress factors [26][25][27]. However, these models are restrictive since they take into account only one aging factor as in the case of the Arrhenius law, or two factors as in the case of Crine's electrothermal model. As in practice insulation lifespan is sensitive to numerous factors and their interactions, these models should include several parameters related to the studied material. Nevertheless, these models generally require complex experimental setups in order to estimate the physical properties of the studied materials and the required tuning constants. They are obtained in labs on samples and, so far, this protocol seems inappropriate concerning parts of stators. No comprehensive method has been proposed to take into account all the stress factors and their interactions in a single batch of experiments.

An alternative way to address this problem is to develop lifespan models based on experimental measurements, *i.e.* mathematical models that fit the experimental data. This methodology is called *regression*. The choice of the lifespan forms and factors remains critical for the model to be accurate. Physical knowledge of involved phenomena may help to choose the appropriate form and factors. For example, a log-based relationship for frequency and voltage and an exponential form for temperature are widely used in the literature [28][29][18] .The accuracy of the model also depends on the choice of experimental measurements (range, levels). The average insulator lifespan under normal operating conditions is of several thousand hours therefore carrying out full ageing tests would be far too expensive.

B. *Organized experiments*

The Design of Experiments method (DoE) is a systematic and efficient method to organize the experiments in order to optimize a process or to estimate a model [30]. Recent literature provides a large number of papers using DoE for various item optimization e.g., machine rotor or inverter in PV systems. DoE helps to reduce the cogging torque and operating torque ripple in [31] [32] through Finite Element Analysis (FEA). Besides, [33] aims at optimizing the reliability in inverters for photovoltaic systems. An inverter is designed several times in order to increase the reliability, with a desired mean time between failures of 12 years. DoE is sometimes combined with other optimization methods. Transformers are optimized in [34] with regard to the iron and copper mass thanks to a multi-objective design which associates a pattern search optimization technique and the Taguchi methodology. Design of Experiments (DOE) is combined with

Differential Evolution (DE) algorithms for the multi-objective design optimization of ferrite magnet machines with fractional-slot concentrated windings in [35]. DoE and the sequential subspace optimization method are presented in [36] to improve the optimization efficiency of a permanent-magnet transverse flux machine with a soft magnetic composite core. But one of the most promising and simple associations is based on DoE and Response Surface methodology. [37] uses both for the design of a hybrid magnetic planetary geared permanent brushless magnet for electric vehicle application. Whatever the option, optimization or modeling, the main objective of DoE is to maximize the model accuracy while minimizing the number of experiments. This method is especially interesting when a large number of factors are involved. Coupling effects between the different factors can be taken into account and the most influential factors can be identified. The principle of DoE is to assign *m* levels to each factor and to organize the experiments according to different configurations such that each factor level is equitably distributed over these configurations. For *k* factors, the total number of experiments is then defined as $n=m^k$. The levels are normalized between -1 and +1 in relation to the real constraint values. Table I illustrates this technique in a very simple case of two factors F_1 and F_2 with two levels. Level -1 is for the low constraint and +1 for the high one. The average response of the system for all experiments is denoted *M*. For each experiment *i*, the response y_i is measured. It is interesting to note that the level of the interaction between the 2 factors I_{12} is computed as the product of the factor levels.

TABLE I
Example of an experimental plan for the DoE method with 2 factors and 2 levels each

Experience Number	M	F_1	F_2	I_{12}	Reponse Y
1	1	-1	-1	+1	y_1
2	1	-1	+1	-1	y_2
3	1	+1	-1	-1	y_3
4	1	+1	+1	+1	y_4

In this case, the mathematical model relating the response *Y* with the different factors is expressed as in (2):

$$Y \sim M + E_1F_1 + E_2F_2 + E_{12}I_{12} \qquad (2)$$

where E_j denotes the effect of factor F_j and E_{ij} denotes the effect of interaction I_{ij}. According to eq. (2) each factor or interaction affects the average lifespan, proportionally to its level value. A linear lifespan model is indeed computed from the lifespan measurements on the extreme constraints of each factor which can be seen as the boundaries of the factor domain. In practice, the effect vector $\hat{E} = (M, E_j)^T$ is computed as in (3):

$$\hat{E} = X^{-1} \cdot Y \qquad (3)$$

with $X = (M, F_1, F_2, I_{12})$ the level matrix and $Y=(y_i)$ the vector of the average measured lifespan for the different tested configurations. DoE provides an appropriate model estimation if the hypothesis of a linear relationship between the response, the factors and their interactions is valid. The Response Surface Method (*RSM*) extends the DoE model to non-linear relationships between factors by considering the quadratic effects of the main factors [38]. RSM also organizes the experiments to minimize their number. However, RSM needs more experiments than DoE because more effects are taken into account. The most popular design of RSM is the Central Composite Design (*CCD*) depicted in Fig. 3 for three different factors. The CCD can be seen as DoE configurations (black points in Fig .4. plus extra points at the center (level 0) and at the boundaries of the factors' domain (red points). In order to ensure the model orthogonality and to reuse the previous DoE points, the extra levels are chosen equal to +/- $\sqrt{2}$ [39]. Each factor is evaluated on 5 levels: $[-\sqrt{2}; -1; 0; +1; +\sqrt{2}]$.

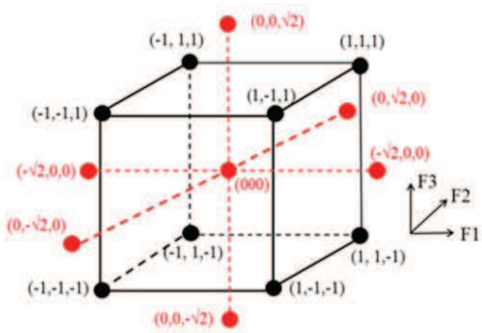

Fig. 3. Central composite design for 3 different factors

The factor effect vector $\hat{E}$ is computed similarly to DoE according to (4) with *X* the configuration matrix. The difference is the computation of *X* pseudo-inverse since it is no longer a square matrix.

$$\hat{E} = \left(X^T \cdot X^{-1}\right) \cdot X^T \cdot Y \qquad (4)$$

It has been proven in [39] [40] that RSM actually improves the DoE lifespan modelling of electrical insulation but at the cost of doubling the number of experiments. As for an optimization option, DoE has already been used for modeling different phenomena. A model of the temperature rise in induction machines is achieved thanks to this method combined with RSM [41]. Experiments involving speed and load as factors in a CCD for a second-order fitted model with good correlation between the model and the experimental results regarding the temperature rise. A complex modeling problem is solved with DoE and genetic algorithm in [42] for a squeeze film haptic tactile feedback actuator. As FEM models exist for a few special cases, an empirical model of the force generated on the user's finger is given.

C. *Random experiments*

When experiment organization is not required or not possible, Multiple Linear Regression (MLR) offers a more flexible methodology than DoE or RSM for lifespan modeling [43]. The MLR method estimates the parameter of a linear model relating the response Y and the p so-called explanatory variables from n experiments that can be randomly chosen. The only conditions regarding experiments are their number, which must be higher than the number of explanatory variables ($n>p$), and that they must be independent. Contrary to DoE and RSM, MLR models involve true factor values instead of levels. In the general case, the model can be expressed as (5):

$$Y = \sum_i \beta_i \cdot X_i + u \qquad (5)$$

where $\{X_i\}_{i=1..p}$ denotes the explanatory variables, $\{\beta_i\}_{i=1..p}$ denotes the model parameters and u denotes the error term. The model parameter vector β can be estimated from the experiments by the ordinary least squares method. The parameter vector estimates $\hat{\beta}$ to be derived as follows in (6):

$$\hat{\beta} = (X^T \cdot X^{-1}) \cdot X^T \cdot Y \qquad (6)$$

In our case, Y denotes the vector of the measured insulation lifespan logarithms. X denotes the matrix of the associated factors or explanatory variable values. Considering a very general model, the explanatory variables can be the logarithm of the electrical stress factors ($log(V)$, $log(F)$), an exponential form of the temperature ($exp(-bT)$) as well as quadratic forms of these variables and/or interactions between these variables. However, the MLR method does not impose a particular model structure, contrarily to the DoE and RSM methods. Thus, the first advantage of the MLR method is that an appropriate model can be selected from performance comparison of different models on a test set. The model can be either linear (constant and linear terms), linear with interactions (constant, linear, and interaction terms), quadratic (constant, linear, interaction, and squared terms) or pure quadratic (constant and squared terms). Moreover the influence of the explanatory variable ranges on the model performance can also be studied.

Indeed a single model can hardly represent the behavior of the studied material under mild to extreme operational conditions. For instance, we can alternatively restrict the study to the shortest, highest and medium lifespan by an appropriate choice of the factor ranges and compare the associated performance. It is then possible to perform regression on particular ranges independently. Moreover, the MLR framework provides a more systematic solution to solve this problem by considering multiple-regime regression [44]. Regression model performance depends on the accuracy of the measurements performed during the experiments. Ordinary least squares estimates for regression models are highly sensitive to so- called outliers. Outliers can occur in practice for many reasons including inaccurate measurements, measurements from a process that is not running under the assumed specifications, and/or a failure mode that is not totally understood. Quantitatively, an outlier can be defined as a data point which falls outside the +5% tail area of the k assumed sampling distribution.
However, the MLR method can be modified to address this point, leading to so-called robust regression methods. The principle of robust regression is to iteratively apply a weighting function on high variance residuals in order to minimize the impact of outliers [45]. Figure 4 shows examples of Huber (on the left) and bisquare (on the right) weighting functions.

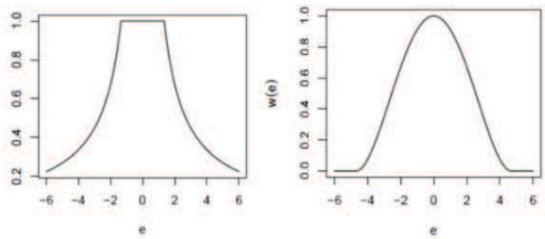

Fig. 4. Huber (on the left) and bisquare (on the right) weighting function

Robust regression has been used for fitting failure-time data plotted on a computer-generated probability plot [46]. Robust regression algorithms performed better than Ordinary Least Squares (OLS) in most data sets and were particularly effective in situations involving early contiguous failures. However, probability plots are intended to infer the lifetime statistical distribution in given operating conditions. In the context of direct multilinear regression of the lifetime with respect to multiple factors, the robust methods have been compared to the OLS approach for the lifespan modeling of insulated twisted pairs in [47]. The performance remains better with ordinary least squares than with robust regression. Indeed, robust regression is not appropriate for small sample sizes [48]. Moreover, in the particular case where several measurements are available for the same experiment configuration, outliers can also be identified using some basic statistical considerations (regarding measurement variance on a given experiment for instance) and removed. Suppression of outliers leads to better performance than robust regression in this case. Replacing such groups of measurements by their medians is also a robust alternative leading to equivalent performance. As a conclusion, the MLR method is far more flexible than DoE and RSM since the experiments can be randomly chosen and appropriate models for particular factor ranges can be selected. On the other hand, DoE and SRM outperform more accurate models with fewer experiments.

D. *Significance tests*

Multilinear regression provides a framework for factor significance analysis and appropriateness of the model assessment [49]. Covariate statistical significance can be checked by an F-test of the overall fit, followed by t-tests of individual parameters. The P value measures the correlation

between a given covariate and the response. In the case where interactions are taken into account, some particular tools are also available [50]. Goodness of fit can be measured using residual analysis and hypothesis testing. The R-squared of the regression, equal to the fraction of the variation of the response that is predicted by the covariates, provides a quantitative measure of the appropriateness. Moreover the significance of each factor effect (or interaction effect) must be evaluated. ANalysis Of VAriance (ANOVA) [51][40] is a good candidate to check whether the model coefficients are significant or not. ANOVA is a widely used statistical model able to separate in two parts (the random and systematic factors), the total variability found within a data set into two components Prior to using ANOVA, two conditions must be verified:

- data must be normally distributed for each factor, which can be achieved using a Shapiro-Wilk test [52],
- the different data must be independent.

Variance V_i due to the specific factor i is compared to the variance of the whole experimental data set, called residual variance V_r. A factor is not significant if its variance V_i is very close to V_r. On the other hand, variance V_1 of a significant factor is higher than the residual variance V_r. The ratio $F_{exp}=V_i/V_r$ is computed and tested using a Fisher-Snedecor test. The effect of factor i is considered as statistically significant if F_{exp} is greater than F_{lim}. Threshold F_{lim} could be found in the table of upper critical values of the F-distribution depending on the degree of freedom of the data and the test significance level (generally 5%).

VI. Test Benches

Two test benches have been successively used in our lab in recent years. Kapton films as in Fig. 5 were submitted to sinusoidal voltage with or without DC part, for different temperatures and frequencies on a first test bench.

Fig. 5. Kapton films under tests

Fig. 6. Tested 90µm coated steel plate (15cm x 9cm) with polyesterimide (PEI)

This first study validated the DoE potential for lifespan modeling. DC voltage was found to have no significant effect on lifespan. Then, coated steel plates (15cm x 9cm) with 90µm polyesterimide (PEI - thermal class: 180°C) as in Fig. 6 were tested in [53] in a climatic chamber.

Fig. 7. The experimental setup for accelerated aging tests, climatic chambers and power electronic

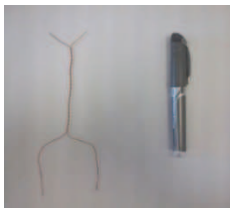

Fig.8. Twisted pairs EDERFIL C200

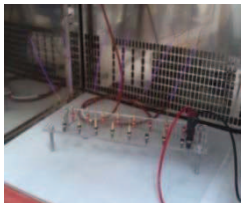

Fig. 9. experimental arrangement of the twisted pairs in the climatic chamber

A second test bench Fig. 7 produces square-wave high voltage (with 10kV/ms as rise time) for two-level DoE. The studied factors are voltage amplitude, frequency and temperature. Tested samples were placed in a climatic chamber with full temperature control. The same equipment supplied 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, 0.5mm diameter), as shown in Fig. 8 and Fig. 9 in [40][39]. These twisted pairs are manufactured according to the American National Standard (ANSI/NEMA MW 1000-2003, Rev. 3, 2007).

V. Results

A. Different Models

According to DoE, experiments are organized in a specific matrix, first part of Table III, named DoE. It involves eight combinations of the three stress factors with two levels each, i.e. 2^8 experiments. The number of required experiments is minimized and model accuracy increases. The expected lifespan model is expressed in (7):

$$Log(L)_{DoE} = M + E_V.Log(10V) + E_F.Log(F) + E_T.exp(-bT) + I_{VF}.Log(10V).Log(F) + I_{VT}Log(10V).exp(-bT) + I_{FT}.Log(F).exp(-bT) + I_{VFT}.Log(10V).Log(F).exp(-bT) \quad (7)$$

Note that the model form between Log(L) and, Log(V), Log(F) and exp(-bT), were chosen in agreement with IEC 60013 standard [13] for V and F and IEC 60216-1 standard for T [17].

The Response surface (RS) method extends the DoE model and improves its accuracy with quadratic terms. The lifespan model becomes (8):

$$Log(L)_{RS} = Log(L)_{DoE} + I_{VV}Log(10V)^2 + I_{FF}Log(F)^2 + I_{TT}exp(-2bT) \quad (8)$$

Therefore, three additional levels are required. The design configuration was specified according to Central Composite Design defined by:

- a complete 2^3 DoE design,
- two axial points on each factor axis at a distance μ from the center, i.e. two extra levels ($\pm\mu$),
- n_0 central points, i.e. all the factors at 0 level,

n_0 and μ values are 4 and $\sqrt{2}$ respectively, so that the obtained design is orthogonal. Thus, the total number of required experiments is 18. Table II displays the different configurations of the experiments required by DoE and RS methods. Factor levels are defined in Table III.

TABLE II
Levels of the Stress Constraints Required for DoE and RS

Experiences		Level for factor V	Level for factor F	Level for factor T
RS	DoE	-1	-1	-1
	DoE	-1	-1	1
	DoE	-1	1	-1
	DoE	-1	1	1
	DoE	1	-1	-1
	DoE	1	-1	1
	DoE	1	1	-1
	DoE	1	1	1
	Axial Point	$-\sqrt{2}$	0	0
	Axial Point	$\sqrt{2}$	0	0
	Axial Point	0	$-\sqrt{2}$	0
	Axial Point	0	$\sqrt{2}$	0
	Axial Point	0	0	$-\sqrt{2}$
	Axial Point	0	0	$\sqrt{2}$
	4 Central Points	0	0	0

TABLE III
Normalized Levels of the Stress Factors

Levels	Log(10V) (kV)	Log(F) (kHz)	Exp(-bT) (°C)
$-\sqrt{2}$	Log(10*1)	Log(5)	Exp(55b)
-1	Log(10*1.174)	Log(5.872)	Exp(34.82b)
0	Log(10*1.73)	Log(8.7)	Exp(26.7b)
+1	Log(10*2.554)	Log(12.77)	Exp(-119.74b)
$+\sqrt{2}$	Log(10*3)	Log(15)	Exp(-180b)

B.

B. DoE results

The first lifespan model is derived from only 8 experiments according to the DoE method. The model is applied on 24 extra experiments included in a validation set. The estimated parameters (average lifespan *M*, factor effects and interaction effects) are given in Fig. 11.a. Comparison between measured and predicted lifespans could be seen in Fig. 11.b. The most influential factors are easily identified: voltage and temperature. Additionally, their interaction is the most influential with respect to the other interactions. Calculations have been made with different criteria: average value of the 6 lifespans in an experiment, median value or according to Weibull distribution. Some of the measured lifespans are far from the average value. They could be considered as outliers, i.e. values out of the expected range susceptible to cause a bias in the model. Moreover, they have a significant influence on the mean value because the population is very small. Medians are preferred as they are more robust to extreme values than averages [54]. Relative errors between predicted and measured responses in the test set range from 0.8% to 234% with an average value of 31%. For example, the test of a model based on the average values rather than the medians leads to an average error of 38%, min error of 1.3% and maximum of 324%.

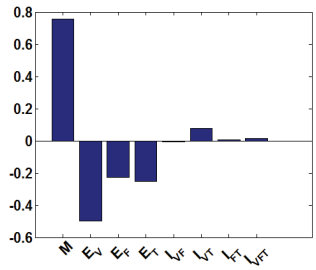

Fig. 11a. DoE model: estimation of factor and interaction effects

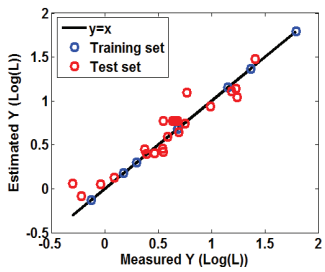

Fig. 11b. DoE model: comparison measured /estimated lifespans

C. RS model

The factor effects obtained by the DoE model reflect reality regarding the high influence of voltage and temperature. However, the model seems to be insufficient since some test points present significant errors (>100%). The model is thus extended by adding quadratic terms, leading to the RS model. The training set consists of 18 experiments and results are in Fig. 12.a and Fig.12.b.

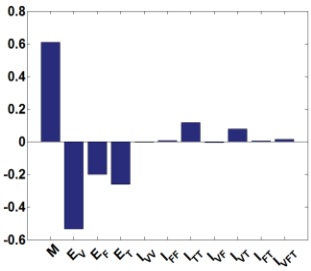

Fig. 12a. RS model: estimation of factor and interaction effects

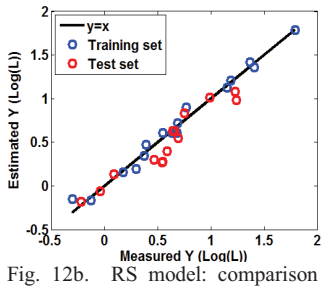

Fig. 12b. RS model: comparison measured / estimated

In addition to the high effects of V, T and their interaction, the RS model reveals a significant contribution of the quadratic term T^2. The maximum and average relative errors computed on the test set decreases to 53% and 25% respectively. In this case, they remain higher with the average values compared to those of the medians Thus, this model is more accurate since it takes more significant effects into account and leads to lower errors. Moreover, our results fit those of "*Table 1–Influence of features of the*

converter drive voltage on acceleration of ageing of components of Type II insulation systems" in [13], where it is stated that fundamental frequency is less influential than the voltage. But it is important to notice that the highest relative errors are for the shortest lifespans which are not our main interest. For example, if the test set includes only lifespans longer than 3mn, minimum, average and maximum errors become respectively 0.4%, 5% and 18%.

D. MLR results

Fig 13.a and Fig.13.b present the results obtained with Multi Linear Regression. The relative errors between the model outputs and the validation test range from 0.15% to 193%, with an average error of 22%, which are of the same order of magnitude than those of the DoE or RSM.

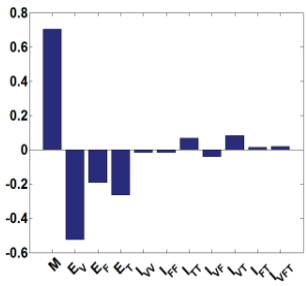

Fig. 13a. MLR model: estimation of factor and interaction effects

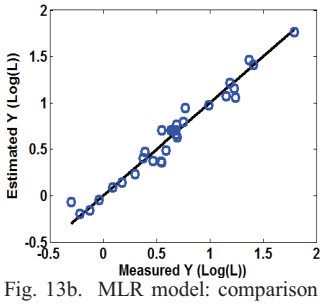

Fig. 13b. MLR model: comparison measured / estimated lifespans

VIII. CONCLUSION

The problem of lifespan modelling for insulation systems of electrical machines was adressed in this paper. Three different insulation materials were tested, kapton films, polyesterimide films and enameled twisted pairs. It was shown that several regression methods are able to provide satisfying multiconstraint models. DoE and RSM are the most accurate with a limited experimental cost, while multi linear regression is more flexible as it does not require organised experiments.

Future work will take into account rise time rather than frequency, pressure and temperature cycling. As a consequence, the number of factors will dramatically increase and DoE will be a very useful method. Nevertheless, several points remain an issue. Results have been given for lifetime but aging modelling is still pending. As PWM inverters can involve more than 3 levels, multi level contraints could be included in the scope of the study. Finally, parts of real stators should be tested rather than samples, but the very limited number of specimen remains a challenging problem.

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X. BIOGRAPHIES

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