Available online at www.sciencedirect.com
ScienceDirect
Mathematics and Computers in Simulation 131 (2017) 200–216
MATHEMATICS AND COMPUTERS IN SIMULATION
www.elsevier.com/locate/matcom

Original articles

# Regression methods for improved lifespan modeling of low voltage machine insulation

F. Salameh[a,*], A. Picot[a], M. Chabert[b], P. Maussion[a]

[a] *University of Toulouse, LAPLACE-INPT-ENSEEIHT-CNRS-UPS, 2, rue Camichel 31071 Toulouse, France*
[b] *University of Toulouse, IRIT-INPT-ENSEEIHT-CNRS-UPS, 2, rue Camichel 31071 Toulouse, France*

Received 15 October 2014; received in revised form 13 May 2015; accepted 1 November 2015
Available online 2 December 2015

**Abstract**

This paper deals with the modeling of insulation material lifespan in a partial discharge regime under certain accelerated electrical stresses (voltage, frequency and temperature). An original model, relating the logarithm of the insulation lifespan, the logarithm of the electrical stress and an exponential form of the temperature, is considered. An estimation of the model parameters is performed using three methods: the design of experiments (DoE) method, the response surface method (RSM) and the multiple linear regression (MLR) method. The estimation is obtained on learning sets determined according to each method specification. The performance, in terms of estimation, of each of the three methods is evaluated on a test set composed of additional experiments. For economic reasons and flexibility, the learning and test sets are composed of experiments carried out on twisted pairs of wires covered by an insulator varnish. The ability of the DoE and the RSM methods to organize and to limit the number of experiments is confirmed. The MLR method, however, shows more flexibility with regard to the studied configurations. Thus, it offers an efficient solution when organization is not required or not possible. Moreover, the flexibility of MLR allows specific ranges for the factors to be explored. A local analysis of the estimation performance shows that very short and long lifespans cannot be simultaneously represented by the same model.


*Keywords:* Lifespan; Twisted pairs; Design of experiments; Response surface; Regression

## 1. Introduction and problem formulation

New applications in aeronautics, especially in more electric aircrafts, should widen the use of low voltage (under 1 kV) electrical rotating machines. Consequently, the lifespan of these machines becomes a key issue for aircraft reliability assessment. Approximately 40% of the failures in low voltage rotating machines originate from the stator-winding insulation materials [29]. For these reasons, this paper focuses on insulation lifespan statistical modeling.

The objective is to provide a reliable lifespan model under extreme conditions for further lifespan prediction under nominal conditions. For economic reasons and flexibility, experiments were conducted on twisted pairs (entwined copper cords, coated by an insulator varnish) as they are expected to behave in a similar manner to the stator-winding

* Corresponding author.
*E-mail address:* salameh@laplace.univ-tlse.fr (F. Salameh).

http://dx.doi.org/10.1016/j.matcom.2015.11.001
0378-4754/

insulator with respect to thermal and electrical stresses. Obviously, the study of mechanical stress influence would require different devices to be tested. However, a mechanical stress study is out of the scope of this paper.

Considering the average device lifespan (several thousands of hours under nominal stress), carrying out full aging tests would be too expensive. Accelerated Life Testing (ALT) allows us to tackle this problem [15,24,30]. The principle of ALT is to test the components under combinations of higher-than-usual levels of the stress lifespan variables (e.g. rate of use, temperature, voltage or pressure) in order to bring the lifespan below an acceptable level. The purpose is to obtain information about the failure-time distribution at specified levels of these variables. Then, data from these tests are extrapolated, through a physically reasonable statistical model, to obtain estimates of lifespan or long-term performance at lower, nominal levels of the stress variables [2]. This kind of test has been used for different objects in electrical engineering such as insulated gate bipolar transistor (IGBT) modules in high temperature power cycling [27] or nano-structured enamels on twisted pairs [8]. In this paper, ALT is applied to the lifespan modeling of insulating materials.

The lifespan of components used in electrical or electronic engineering has been modeled as a function of a given factor according to the Arrhenius law (temperature) [6,9], according to the inverse power law (voltage or pressure) [6,25,32], or according to the Coffin–Manson law (temperature cycling) [2], for instance. Lifespan models involving several factors have also been proposed such as the Crine model (electrothermal stress) [6,17], the Hallberg–Peck (temperature and humidity) [2,26] or the Eyring (electrothermal stress) [2] models. Unfortunately, these models are limited to two factors only. Moreover, they generally require the prior knowledge of some physical properties of the studied material or of particular constants (for instance, the activation energy in the case of Arrhenius law and Eyring model or some thresholds regarding the applied stresses in the case of the inverse power law, etc.). The estimation of these quantities depends on the studied material [2]; it generally requires complex experimental setups and is only valid for a given stress range [30].

Empirical models which relate multi-stress levels to insulation lifespan have also been developed. For instance, the Simoni model [21] and the Ramu model [6], derived from the general Eyring model, the Fallou exponential model [6] and the Montanari probabilistic model [20] allow us to describe insulation aging processes occurring in particular stress ranges. However, these so-called multi-factor models are in fact limited to two factors: the electrical and the thermal stresses.

Consequently, the existing lifespan models have been applied on a variety of electrical components and materials. However, they often remain too simplistic since they are restricted to a single factor or two factors and are only valid for particular factor ranges. Moreover, they do not provide an explicit term for the interaction between factors. In real-life operations, materials are subjected to a multitude of operational and environmental stressors acting simultaneously. Thus the contribution of each stressor to material lifespan reduction cannot be studied independently from the others. The synergetic effects, including interaction or coupling terms, should be taken into account for a more realistic modeling of real operation conditions. Finally, these state-of-the-art lifespan models require a specific experimental setup and procedure for each studied material. To our knowledge, there has been no unification approach for the development of these models before now.

In this paper, we introduce a new statistical approach for the modeling of lifespan that can be applied to different types of insulating materials [15,24,30], with no prior knowledge of their physical properties. Contrary to the existing models, the proposed lifespan models include all possible interactions between the factors and they consider wide variation ranges. Experiments are based on ALT and involve three main aging factors (voltage, frequency and temperature) as they have been identified as the predominant aging factors. The number of experiments and their configuration are fully specified according to a design method under the constraint of a reduced number of experiments.

The first model studied in this paper includes the interactions between factors using the Design of Experiments (DoE) method [3,15,24,30]. The second method, the Response Surface Method (RSM) [12,22,24,30], is applied to improve model accuracy by adding the quadratic forms of the factors. The proposed methodology, based on DoE and RSM, has already been applied in [15,24] and validated for the lifespan modeling of insulating Poly-Ether-Imide (PEI) films of thermal class 180 °C. This paper shows that the same methodology can be applied to different material: the twisted pairs of wires covered with a double layer of insulating varnish of Poly-Ether-Imide (PEI) and Poly-Amide-Imide (PAI) of thermal class 200 °C.

In addition to the DoE and RSM methods, this paper considers lifespan modeling as a Multiple Linear Regression (MLR) problem [30,31] where no specific experimental design is required. The results obtained using these three different methods are analyzed and compared. The predictability of the models is studied with respect to the insulator