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Real-Time Insulation Lifetime Monitoring For Motor Windings

K. Tshiloz, A. C Smith, A. Mohammed, S. Djurović and T. Feehally

Abstract – This paper investigates the development and implementation of a real-time thermal ageing model for polymer-based electrical wire insulation using the classical Arrhenius relationship for chemical reaction rates. The paper presents the theoretical development and implementation of the method for predicting the insulation lifetime based on real-time temperature measurements using fibre-optic sensors embedded inside copper-wound coils. The performance of the presented lifetime model in delivering consistent results for winding insulation lifetime predictions is then assessed and validated using real-time steady-state and transient thermal experiments on a wound test coil mounted into a purpose built motorette test rig.

Index Terms— Coil, fibre-optic, insulation lifetime, model, motorette, real-time, sensor, steady-state, transient and thermal ageing.

I. INTRODUCTION

ELECTRICAL machines are essentially wound components for modern industrial systems. During operation, the insulation materials in electrical machines are exposed to thermal stresses. These thermal stresses initiate progressive degradation of the insulation materials, which lead to the deterioration of the insulation characteristics and consequently to insulation breakdown [1]. Therefore, knowledge relating to the condition of the insulation systems and an estimation of the remaining life has become an important concern to manufacturers and users of electrical systems [2]. Real-Time lifetime prediction of insulation materials is of interest in this work. Severe winding insulation breakdown due to thermal stresses have been reported as contributing to as much as 30-40% of all stator winding failures in conventional induction machines [3]. It was also reported in [4-6] that thermal ageing is the dominant ageing factor and can contribute up to $\approx 31\%$ of the deterioration of the insulation materials.

The lifespan of the insulation is usually predicted using accelerated ageing tests. An accelerated ageing test is used in

the effort to obtain failure statistics in shorter timescales. In [2, 7], the lifetime of the insulation material was estimated using an electro-thermal ageing model that takes into account the combined electrical and thermal stresses in the lifetime prediction. Real-time insulation lifetime predictions during steady-state and transient operating conditions of wound components have received less attention in the available literature.

The thermal ageing model based on the classical Arrhenius relationship can be adapted for real-time steady-state and transient thermal ageing predictions of the insulation materials for wound components. The key input to the insulation lifetime model is the measured temperature distribution around the winding insulation.

Winding temperatures are conventionally sensed using thermocouples or resistance temperature detectors embedded on the exposed external surfaces of the electrical machine and/or windings [8]. These techniques commonly provide single-point temperature measurements that are often unreliable [8]. Moreover, these sensors come with significant challenges imposed by the location of the sensors close to or within the stator windings for example due to use of electrically conductive materials in the sensor packages as well as susceptibility to electromagnetic interference [8]. The key objective in this work is to access the capability of predicting real-time remaining life of wound components insulation materials using Fibre Bragg Grating (FBG) sensors embedded directly into the stator coils during fabrication. The FBG sensors are fibre-optic sensors that have been used in other applications, ranging from frame vibration sensing of the stator core and coil surface thermal monitoring [9-12]. The FBG sensors are small and can be laid into the middle of the coils during the wind process and can provide real-time temperature information at several measurement points around the coil length in a single fibre. The FBG sensor has the inherent advantage of electromagnetic interference immunity making it a strong candidate for enabling reliable real-time temperature measurement in wound components. The performance of the insulation model in delivering reliable real-time lifetime predictions is assessed by direct comparison with the standard lifetime of conventional class H winding insulation. The thermal ageing algorithm is implemented on a SmartScan 04 Dynamic FBG Interrogator real-time platform. The model performance is evaluated on a purpose built motorette test rig. The presented ageing model is shown to have good potential for providing remaining real-time lifetimes of wound components under varying temperature which is representative of a motor under varying load conditions.

II. EXPERIMENTAL SET-UP

Experimental work was performed using laboratory motorette test rigs built to house prototype multi-turn coils for testing along with suitable coil bobbins to wind the coils in a reasonable standard regular pattern. The bobbin was built to

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Fig.1: a) Built coil bobbin, b) Proposed positions for FBG temperature sensors embedded in middle of the coil

wind random coils using an existing coil winding rig available in the laboratory. The manufactured bobbin can be easily dismantled to allow the removal of the test coil without damaging the insulation. The winding speed was kept low in order to increase the wire tension and produce coils with a reasonable packing factor of $\approx 40\%$ [13]. The dimensions of the motorette are given in IEEE standard 177 [14].

The distance between the two parallel sides at the middle of the coil is $\approx 51\text{mm}$. The number of turns of the coil was 40 turns made from 0.9mm diameter standard Class H enamel copper wire and the temperatures were measured using a single fibre-bragg sensor embedded into the test coil as shown in Fig.1a. The temperature signals were recorded and processed using a SmartScan 04 Dynamic FBG Interrogator platform [15]. The SmartScan 04 can dynamically measure the wavelength in nanometres of the fibre-optic sensors in the fibre caused by the temperature variations. The measured wavelengths are then processed using a LabVIEW code to obtain the real-time temperatures. The real-time temperatures are then fed into the thermal ageing model described in section IV to obtain real-time lifetime predictions of the insulation materials. The SmartScan 04 has a scanning frequency of 2.5 kHz with a wavelength resolution of less than 1 picometre [15]. A programmable Sorensen SGI 100/50 DC power supply [16] was used to energise the test coil with a DC current in order to investigate different dynamic thermal ageing tests.

The main advantage of this coil system is being able to embed temperature sensors directly into the middle of the coils where the highest temperatures occur and provide real-time temperature measurements that can be fed back to the drive controller as an operational control input. The real-time temperature feedback can then be processed in the drive controller to predict the remaining lifetime of the coil based on the measured winding temperature insulation. The FBG sensors are small (diameter = 0.25mm) and can be easily laid into the middle of the coils during the winding procedure as illustrated in Fig.1a. The proposed positions of the FBG sensors are shown in Fig.1b. Two sensing positions in the fibre (FBGB and FBGD) were embedded in the centre of the coil, while the other two sensing positions (FBGA and FBGC) were positioned at the coil ends which would be representative of the end-windings in a machine.

III. REAL-TIME TEMPERATURE MONITORING

To evaluate the performance of the FBG sensor, the average measured temperatures of a different coil to the one shown in Fig.1 were compared to the measured reference temperature obtained using a standard K-Type thermocouple placed on the exposed outer surface of the wound test coil. The measured average values are summarised in Table I. The measured average values show a consistent and accurate correlation between the different measurement points on the fibre and the thermocouple. The thermal monitoring system of the embedded FBG sensor was evaluated using a number of steady-state and dynamic thermal ageing experiments based on the international standard IEC 60034-1 [17]. Initially, steady-state experiments were performed by injecting a DC current of $\approx 6.9\text{ A}$ into the coil mounted in the motorette shown in Fig.1b. The DC current of $\approx 6.9\text{ A}$ was found to produce a temperature of $\approx 177^\circ\text{C}$, just below the rated temperature value (180°C) for Class H winding insulation. The temperatures were then measured on a second prototype coil with FBG sensors only and recorded for ≈ 300 seconds during a steady-state test and are shown in Fig.2.

The motorette was then tested using a time-varying current and temperature to assess the performance of the FBG sensors under dynamic conditions. A sequence of identical on-off duty cycles, each cycle consisting of operation at a constant load current of $\approx 7.3\text{ A}$ was undertaken. A LabVIEW code was developed to control the programmable Sorensen SGI 100/50 DC power supply using a pre-determined look-up table for the repetitive on-off duty-cycle operation. The experimental temperature variations for the real-time thermal ageing model composed a sequence of 6 consecutive cycles as shown in Fig.3.

TABLE I
MEASURED TEMPERATURES

SENSOR	TEMPERATURE [$^\circ\text{C}$]
K-TYPE THERMOMETER	175
FBGA	175.32
FBGB	176.01
FBGC	176.75
FBGD	176.42

Fig.2: Measured temperatures, $I_{Load} \approx 6.9 A$, FBGs

The experimental cycle injected a constant load current ($\approx 7.3 A$) for ≈ 4 minutes and then no-load current ($0 A$) for ≈ 6 minutes producing $\approx 40\%$ of the cycling duration factor based on the international standard IEC 60034-1[17]. The measured data in Fig.3 shows an initial steady-state temperature of $83^\circ C$ for 93 seconds which was achieved by injecting a preliminary load current of $\approx 3.27 A$. The measured temperature data for the four sensing points FBGA-D was recorded for 60 minutes and show similar temperature patterns with temperature fluctuations of $\approx 103^\circ C$ - $199^\circ C$. The maximum error was estimated to be $\approx 2.71^\circ C$. The measured real-time temperatures demonstrate the capability of FBG sensors for accurate data input to the on-line thermal ageing model.

IV. THERMAL AGEING MODEL

Ageing in insulation of wound components is usually defined as the reduction in the function of the insulating materials [18]. The insulation lifetime is defined when the insulation properties of wound components deteriorate to values such that the wound components cannot operate satisfactory. The commonly used convention is that the lifetime is defined when the insulation strength is reduced to 50% of the initial value at manufacture.

Under thermal stresses the insulation loses its capability because irreversible changes take place in the chemical composition and physical properties of the organic materials. Physical chemists looked at the rate of change of the concentration of certain constituents in chemical combinations in organic materials as a function of time and temperature [18]. This approach can be employed to organic electrical insulation deterioration if we know or assume that the physical properties of the insulation material is proportional to the concentration of an important constituent [18].

$$P = f(C) \quad (1)$$

where: P is the magnitude of the physical property in which we are interested in and C is the concentration of an important chemical constituent of the insulation materials which is being changed by the thermal stresses.

The instantaneous rate of change of the number of molecules undergoing transformation with time is proportional to the number of the molecules. This relates to the chemical reactions of oxidising decomposition, polymerization, bridging and evaporation of plasticiser [18]:

Fig.3: Measured temperatures, transient operation, FBGs

$$\frac{dC}{dt} = -kC^n \quad (2)$$

where: k is the reaction rate constant n is the order or rank of the reaction and t is the time.

The reaction rate constant k is normally assumed to be dependent on the temperature only. Integrating (2) assuming a first order reaction ($n = 1$) gives:

$$C = C_0 e^{-kt} \quad (3)$$

$$\log_e(C) = -kt + \log_e(C_0) \quad (4)$$

Equations (3), and (4), show that the concentration of a chemical undergoing transformation in a first order reaction reduces exponentially with the time. If we directly replace the concentration C by the lifetime of the insulation material, L in (4), the lifetime can be expressed as follows:

$$\log_e(L) = -kt + \log_e(L_0) \quad (5)$$

The reaction rate constant, k is given by the Arrhenius reaction relationship. The Arrhenius reaction relationship describes the dependence of chemical reaction rates on the temperature, and can be used as a basis of thermal ageing model [19]. The Arrhenius reaction relationship can be expressed as follows [19]:

$$k = Ae^{-(E/RT)} \quad (6)$$

where: A is the frequency constant, E is the activation energy, R is the gas constant and T is the absolute temperature.

Fig.4: Thermal ageing model

Substituting the Arrhenius reaction constant, k in (5), and rearranging we get:

$$\log_e(t) = C_1 + \frac{C_2}{T} \quad (7)$$

This equation demonstrates that the logarithm of the lifetime, t , is proportional to the reciprocal of the absolute temperature T and represents the classical expression used to plot the insulation lifetime in hours as a function of the absolute temperature T . Equation (7) can be rearranged to provide a real-time lifetime model under varying temperature conditions as follows:

$$\log_e(L/L_0) = -C_1 t e^{-(C_2/T)} \quad (8)$$

The constants C_1 and C_2 can be obtained using the IEEE standard 177 [14] insulation lifetime data for standard Class A, B, F and H or the wire manufacturer [20] or by test for example [14]. The ratio (L/L_0) in equation (8) represents the reduction ratio of the insulation lifetime from its initial value L_0 at time t for a temperature T .

This thermal lifetime model was implemented on the real-time SmartScan 04 Dynamic FBG Interrogator platform using a LabVIEW virtual instrument (VI) code architecture. The LabVIEW code was developed to measure the real-time FBG sensor wavelengths, convert the measured wavelengths into real-time temperatures and then execute the proposed real-time thermal lifetime model of the wound test coil. The thermal lifetime model flowchart is presented in Fig.4.

V. REAL-TIME LIFETIME PREDICTION

A. Performance Evaluation for Steady-State Operation

The real-time performance of the developed algorithm was tested in a series of laboratory experiments. The laboratory motorette was operated under steady-state conditions to obtain an initial evaluation of the lifetime model. The motorette was energised using the programmable DC power supply. The thermal rating of the class H wire insulation is based on a nominal life of 20000 hours [14, 21]. The lifetime model was used to predict the remaining lifetime of the coil at the steady-state measured temperature of $\approx 177^\circ\text{C}$ presented in Fig.2 and the average measured results are summarized in Table II. As expected the adapted thermal model produces consistent results with the nominal 20000 hours lifetime at 180°C .

The lifetime model was then used for steady-state temperature measurements at a series of different temperature operating points of $\approx 157^\circ\text{C}$, $\approx 167^\circ\text{C}$, $\approx 177^\circ\text{C}$, $\approx 187^\circ\text{C}$ and $\approx 197^\circ\text{C}$ until the rated temperature ($\approx 200^\circ\text{C}$) of the FBG sensor was reached. The average lifetime prediction is summarised in Table III. The obtained results demonstrate as is commonly accepted that for every $\approx 10^\circ\text{C}$ increase in temperature, the lifetime of the insulation material decreases by $\approx 50\%$ [21-22]. The predicted lifetimes shown in Table III are in close agreement with the reported lifetimes of Class H insulation materials given in the IEEE standard 177 [14].

TABLE II
REAL-TIME STEADY-STATE PERFORMANCE, $\approx 177^\circ\text{C}$

SENSOR	AVERAGE LIFETIME [Hours]
FBGA	20085
FBGB	19886
FBGC	20584
FBGD	22010

TABLE III
PERFORMANCE EVALUATION BY $\approx 10^\circ\text{C}$ VARIATIONS

AVERAGE LIFETIME [Hours]				
TEMPERATURE [°C]	FBGA	FBGB	FBGC	FBGD
≈ 157	84162	83382	83738	83277
≈ 167	42258	41240	41016	40807
≈ 177	20085	19886	20150	20195
≈ 187	10570	10295	10286	10176
≈ 197	5102	5061	5080	5056

B. Performance Evaluation for Transient Operation

The real-time performance of the thermal ageing model was also investigated for a sequence of 6 consecutive thermal cycles. The measured temperatures profiles shown in Fig.3 were input to the thermal ageing algorithm and the predicted lifetimes are shown in Figs.5-8. During the thermal ageing experiment, the resistance of the built coil mounted into the motorette increased from its room-temperature value of $\approx 0.39 \Omega$ to $\approx 0.62 \Omega$ which correlates with the calculated resistance of $\approx 0.64 \Omega$ using the temperature coefficient of the copper of ≈ 0.004 per $^\circ\text{C}$. Figs.5-8 show the real-time reduction in the coil lifetime as the temperature cycles up and down between $\approx 103^\circ\text{C}$ and $\approx 199^\circ\text{C}$. The lifetime reduces sharply (marked by sections W1-6 on the figures) when the temperature increases above the rated temperature for Class H wire of 180°C . The total lifetime reduction of the coil predicted by each Fibre Bragg Grating sensor position for the test time period of ≈ 60 minutes are presented in Table IV. The total remaining life predicted using the measured real-time temperature from the four sensing points was $\approx 72\%$ corresponding to a total reduction in the insulation lifetime of $\approx 28\%$. The standardised method assumes a lifetime of 20000 hours and determines the wire thermal rating from this nominal life [14, 21]. If the insulation material of a wound coil operates below the wire thermal rating the lifetime (hours) increases rapidly.

TABLE IV
REMAINING LIFETIME FOLLOWING THE ≈ 60 MINUTES CYCLE

SENSOR	LIFETIME [Hours]		REMAINING LIFE [%]
	NOMINAL	END CYCLE	
FBGA	≈ 198157500	142848860	72.09
FBGB	≈ 198157500	142887397	72.11
FBGC	≈ 198157500	142381614	71.85
FBGD	≈ 198157500	141884546	71.60

Fig.5: Lifetime prediction, transient operation, FBGA

Fig.6: Lifetime prediction, transient operation, FBGB

VI. CONCLUSIONS

This paper develops a thermal ageing model based on the classical Arrhenius relationship for real-time life prediction for insulation materials. The algorithm is aimed at enabling lifetime prediction based on real-time temperature measurements using fibre-optic sensors with measurements taken at multiple locations within one fibre, embedded inside the coils of wound components. The performance of the lifetime model was evaluated using real-time steady-state and transient thermal experiments and was found to produce consistent results for winding insulation lifetime predictions. The real-time thermal model is relatively straightforward to implement and could be embedded directly into the motor controller as part of motor health management system for example.

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Fig.7: Lifetime prediction, transient operation, FBGC

Fig.8: Lifetime prediction, transient operation, FBGD

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