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Effect of the Short-Term Temperature Changes on Diagnostic Indicator In Online Insulation Monitoring by Parametric Identification

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Abstract— Electrical generators of offshore wind or tidal current turbines are exposed to harsh marine and operating conditions. Predictive maintenance is therefore a key issue for the competitiveness of these energy generation systems. Generally speaking, the predictive maintenance is based on the monitoring of a Diagnostic Indicator (DI): the interpretation of its value or drift is used for the optimal planning of the corrective maintenance. In this work, we present briefly our new online monitoring technique of electrical machine winding insulation. This model-based approach consists in monitoring the drift of a DI built from the in-situ estimation of high-frequency electrical model parameters. The involved model structures are derived from the RLC network modeling of the winding insulation, with more or less lumped parameters. In the second part of the work, we investigate the effects of temperature changes on the estimated parameters of diagnostic models. A 1.5 kW low power wound stator is exposed to different temperature levels, from 30°C to 160°C, and for each temperature a series of experimental acquisitions is realized. Identification results show that resistance and inductance of a simple HF model structure are almost independent of temperature changes, while insulation capacitance increases with temperature increases: at 160°C it is 8% higher than its initial value at room temperature.

Keywords— Condition monitoring, Fault diagnosis, insulation, parameter estimation, sensitivity analysis.

I. INTRODUCTION

The recent progress and policy decisions in Marine Renewable Energies (MRE) indicate that offshore wind and tidal current technologies are now mature enough for their industrial deployment over the coming years [1]. However, the harsh marine conditions, such as salty environment, water infiltration and thermal cycling, have brought serious challenges to their operation [2]. For high power electrical generators used in the MRE turbines, the stator rewinding is, without any doubt, the most expensive repair that MRE farm operators will deal with during life service [3]. To avoid the premature degradation of the insulation system that could lead to an unscheduled costly outage, the most efficient way is to continuously monitor the insulation health state[4].

This is the guiding idea of the proposed diagnosis method based on the in-situ estimation of electrical parametric models derived from the RLC network modeling of the winding insulation system [5]. A Diagnostic Indicator (DI) built with

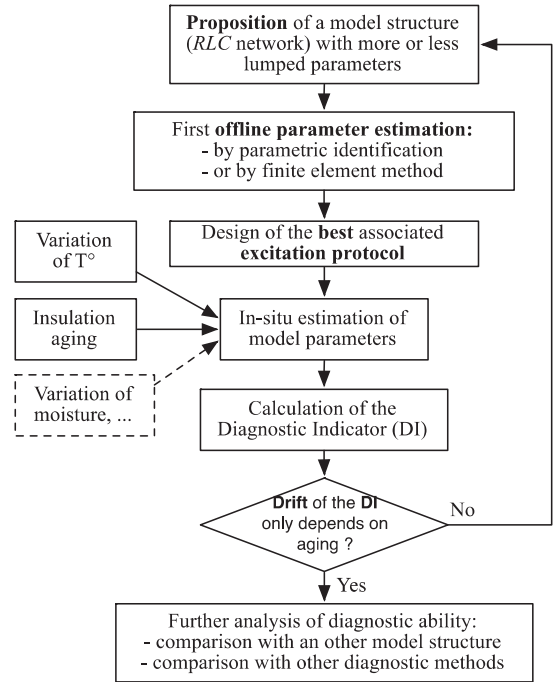


Fig. 1. Guiding principle for the research of a diagnosis model.

the turn-to-turn or turn-to-ground capacitance estimated values can be used for evaluating the health state of the insulation system (see Fig. 1) [6]; indeed it has been shown that the value of these capacitances increases with aging [4], [7], [8]. Unfortunately, consequences of insulation aging, moisture, temperature or skin effect can be mixed in parameter estimated values of too lumped parameter models. Actually, a short-term temperature can affect the high frequency behavior of the insulation, and consequently the DI may depend on the temperature of service. In this work, we investigate the influence of winding short-term temperature changes on estimated parameters of several simple model structures derived from the high frequency input/output behavior of the insulation system. The underlying purpose is to evaluate this dependence and to propose, in further works, model structures that could take into account the difference between insulation aging and temperature variations due to service condition changes. Such structures should present the best tradeoff between simplicity for their identifiability in operating

conditions and complexity for their diagnosis ability. The principle of the in-situ identification of the insulation system is presented in the next section. A short review of the effects of physical characteristics (temperature, frequency and moisture) on the insulation high frequency behavior is proposed in the third section. The last section presents experimental results and discussions.

II. IDENTIFICATION OF THE INSULATION SYSTEM FROM EXPERIMENTAL DATA

A. In Situ Identification of High Frequency Model Structures

Fig. 2 shows the technical solution carried out for the in-situ excitation of the insulation system. A pulse generator applies a high frequency and high voltage excitation to the insulation system, between phases and ground wall. The capacitive coupling box contains adaptation and measurement resistances, and the impedance of the coupling capacitances can be neglected in the high frequency range of the input/output signals used for the insulation system identification.

B. Complexity of the Model Structures

The main concept of this paper deals with the system modeling and parameter identification of diagnosis model structures. For the insulation system, model structures can deal with very simple R-L-C circuits lumped in series or more complex RLC networks that can well explain the propagation of the voltage surges in the whole insulation system [5]. The increase of the structure fineness (i.e. the decrease of the size of the elementary physical volumes modeled by lumped R, L, C elements) tends to improve the physical signification of its parameters, and therefore to increase its diagnosis ability [5]. Furthermore, the more we try to take into account physical phenomena (such as non-linearities or skin effects), the more the structure requires parameters. Finally, a “good” diagnostic model must present the best tradeoff between the structure fineness for its diagnosis ability and the number of parameters for its identifiability in operating conditions.

C. Continuous-Time Model Identification by the Output Error Method and the Sensitivity Functions

1) General Principle

Fig. 3 resumes the principle of the output error method with an output error model [9]: the system output $y_s(t)$ is considered as the sum of the model output for the “right” value of the parameter θ^* and an output noise $b(t)$ which embeds measurement and modeling noise. Let θ be an estimation of θ^* . Then, a simulation of the system output $y_m(t, \theta)$ using only the measured input signal $u(t)$ can be obtained by a numerical

integration of the continuous-time state-space model defined by:

$$M(\theta): \begin{cases} \dot{x}(t, \theta) = f(x(t, \theta), \theta, u(t)) \\ y_m(t, \theta) = g(x(t, \theta), \theta, u(t)) \end{cases} \quad (1)$$

where θ is the parameter vector, $x(t, \theta)$ is the state-vector, the input $u(t)$ and the model output $y_m(t, \theta)$ can be scalar or vector, and the functions f and g are based on physical laws which are generally non-linear with respect to parameters. Bold letters refer to vectors. This general form allows to study linear as well as non-linear model structure (with respect to input), with scalar or vector input and output. Then, the optimal estimated parameter vector θ_o is obtained by the minimization of the following quadratic criterion $D(\theta)$, [9]:

$$D(\theta) = \sum_{k=1}^N e(k, \theta)^T e(k, \theta) \quad (2)$$

where $e(k, \theta) = y_s(k) - y_m(k, \theta)$ is the output error at sample time t_k .

2) Non-Linear Optimization of the Quadratic Criterion

Near the optimum, $\theta = \theta_o + \delta\theta$ and the second order Taylor expansion of the state-distance gives:

$$D(\theta) \approx D(\theta_o) + \delta\theta^T \cdot \underbrace{G(\theta_o)}_{=0} + \frac{1}{2} \delta\theta^T \cdot \mathcal{H}(\theta_o) \cdot \delta\theta \quad (4)$$

where $G(\theta_o)$ and $\mathcal{H}(\theta_o)$ denote the gradient and the hessian of D at point θ_o . The gradient $G(\theta_o)$ cancels at the critical point θ_o , and thus the derivation of (4) with respect to θ gives:

$$G(\theta) \approx \mathcal{H}(\theta_o)(\theta - \theta_o) \quad (5)$$

Multiplying (5) by the inverse of the hessian matrix should allow reaching the objective point θ_o in one iteration from a starting point. Unfortunately, (4) is an approximation of the hyper-surface $D(\theta)$ near the objective point, and therefore multiple iterations are required. One can for example use the Gauss-Newton algorithm [10]:

$$\theta_o^{p+1} = \theta_o^p - \lambda \cdot (\mathcal{H}(\theta_o^p)^{-1} \cdot G(\theta_o^p)) \quad (6)$$

for which the gradient vector $G(\theta_o^p)$ gives the direction of the search in the parametric space, whereas the inverse of the hessian matrix gives the depth of the descent. The calculation

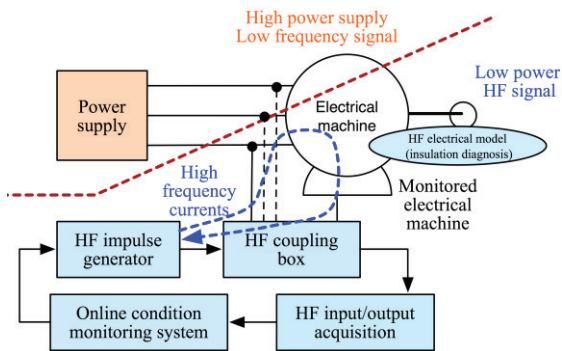


Fig. 2. Online insulation system excitation in the high frequency domain

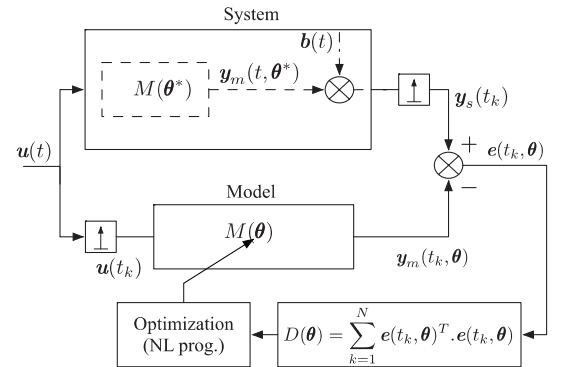


Fig. 3. Principle of the output error method, for a continuous-time model structure and a quadratic criterion.

of \mathcal{H} and \mathbf{G} by numerical derivation would induce dramatic computational problems. A better solution consists in using the sensitivity functions. Indeed, the first and second-order derivative of (2) with respect to $\boldsymbol{\theta}$ gives the following gradient and hessian expressions, which only depend on the measurements, the model simulated output and the values of the output-sensitivity functions [9]:

$$\mathbf{G}(\boldsymbol{\theta}) = -2 \sum_{k=1}^N \psi(k, \boldsymbol{\theta})^T \cdot \mathbf{e}(k, \boldsymbol{\theta}) \quad (4)$$

$$\mathcal{H}(\boldsymbol{\theta}) \simeq 2 \sum_{k=1}^N \psi(k, \boldsymbol{\theta})^T \cdot \psi(k, \boldsymbol{\theta}) \quad (5)$$

where $\psi(k, \boldsymbol{\theta}) = [\sigma_{i, \theta_j}(k, \boldsymbol{\theta})]$ is the Jacobian matrix of $y_m(k, \boldsymbol{\theta})$ and $\sigma_{i, \theta_j}(k, \boldsymbol{\theta})$ is the output-sensitivity function. The detailed methodology of *Output error* method for parameter identification and uncertainty study in the insulation monitoring context is presented in a previous work [6].

III. A SHORT REVIEW OF HIGH FREQUENCY ELECTRICAL BEHAVIOR OF THE WINDING INSULATION SYSTEM

A. Effect of Insulation Aging

Winding insulation aging has been largely studied since the apparition of rotating machines [3]. In the context of online monitoring, recent researches have established a strong relation between insulation aging and the high frequency electrical behavior of insulation system. In [11], the authors showed that the high frequency resonances of a winding insulation change with aging: its variation is correlated with the increase of turn to turn capacitance of insulation. S. B. Lee et al [12] have studied the inter-phases leakage current to evaluate the insulation-condition indicators for simplified insulation model, then a correlation of inter-turn and turn to ground capacitances with aging has been established.

B. Effect of Moisture

Humidity affects the dielectric response in two different ways: first, by penetrating inside the bulk of the insulation, and second by forming a conductive layer of moisture on the insulation surface. Farahani et al investigated in [13] the effects of water content and aging on insulation system response in the frequency domain. They showed that their influence on the capacitance differs in the low and high

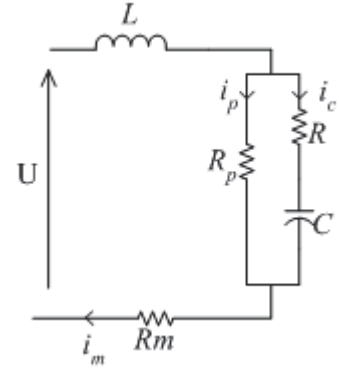


Fig. 5. The proposed model structure of the insulation system

frequency ranges. Humidity affects more the low frequency behavior, while aging effects are more remarkable in high frequency ranges.

C. Effect of Frequency

Frequency dependence phenomena such as the skin and proximity effects on winding electrical parameters are well known, especially in the low frequency range (< 10 kHz). In [14], a finite element model for the calculation of resistance, inductance and capacitance in high voltage machine winding is developed. Comparison between simulated and experimental measurements showed that capacitance is almost independent of the frequency over 100 kHz. The same conclusion is given in [13] [15]. However, the resistance is found strongly dependent on the frequency. It keeps increasing with the frequency increase in all frequency ranges.

D. Effect of Temperature

The effect of temperature on dielectric response of stator winding insulation is quite different, depending on the frequency ranges. R. Soltani et al [16] showed that the capacitance and dissipation factor of insulation materials are more sensitive to temperature variation at very low frequencies (0.1 Hz). However, in relatively high frequency (10 kHz) it is shown in this study and others [17] that the insulation characteristics change, and the degradation rate of the stator winding insulation increases with the temperature swing of the load cycles. Another investigation on the short-term behavior of dielectric response [4] shows that the insulation capacitance and the loss angle first present a fast increase and stabilize after about one hour of heating: this is due to a quick thermal activated insulation conductivity and a slower permittivity.

This short review shows the complexity of dielectric phenomena in the insulation system depending on temperature

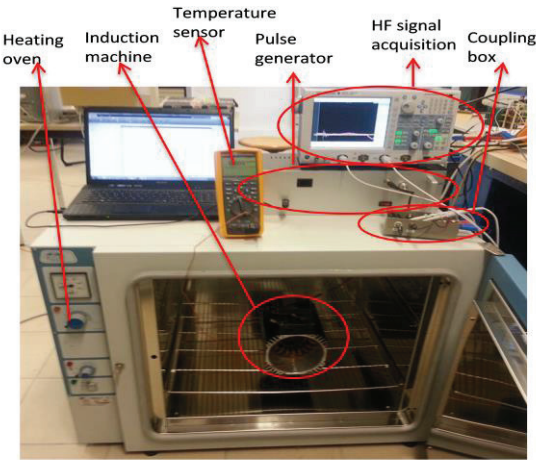


Fig. 4. Experimental bench.

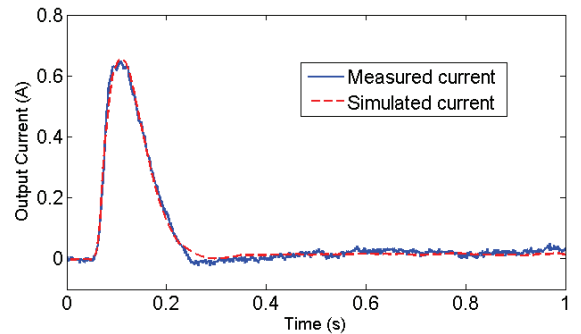


Fig. 6. Experimental measurement for a step excitation protocol

TABLE I. ESTIMATED VALUES OF THE MODEL PARAMETERS

		30°C	40°C	50°C	60°C	70°C	80°C	90°C	100°C	110°C	120°C	130°C	140°C	150°C	160°C
$R_p (\Omega)$	Mean	55.53	55.47	55.72	55.31	55.53	55.58	55.74	55.80	55.92	56.16	56.01	56.2	56.24	55.86
	Std	0.22	0.28	0.18	0.26	0.29	0.24	0.23	0.26	0.24	0.20	0.28	0.25	0.30	0.24
$L (\mu H)$	Mean	1.054	1.075	1.052	1.062	1.045	1.067	1.071	1.074	1.058	1.061	1.065	1.06	1.066	1.047
	Std $\times 10^{-3}$	15.45	10.39	8.59	13.21	16.53	10.83	12.85	9.78	15.19	14.23	11.84	17.0	8.94	13.98
$C_L (nF)$	Mean	0.949	0.938	0.949	0.951	0.959	0.963	0.967	0.979	0.991	0.995	0.100	0.10	0.102	0.103
	Std $\times 10^{-3}$	3.43	2.59	2.89	6.48	1.57	3.68	1.98	5.10	3.36	3.88	2.15	3.01	2.49	4.22

changes, and the interactions with other physical characteristics. The estimated values of HF electrical model parameters may depend on several physical characteristics of the insulation system. The following experimental section details the experimental bench used to investigate the influence of short-term temperature evolutions on diagnosis model parameters.

IV. EXPERIMENTAL STUDY

A. Test Bench

Fig. 4 presents the laboratory bench. The insulation system under test consists in a 1.5 kW star connected machine. The input voltage provided from the pulse generator and the output current charging/discharging the insulation system are acquired by an oscilloscope Yokogawa DL9140, equipped with a 8 bits AD converter rating at 2.5 GHz. Series of ten input/output records are performed at different temperatures, from 30°C±1°C to 160°C±1°C, with 10°C gap. Experimental data are then used to compare the diagnosis potentiality of different model structures. Measurements had been carried outside the heat oven because its walls behave as a Faraday cage and disturb the excitation signal in the high frequency range.

B. Results and Discussions

In this study, several behavior model structures had been investigated. We present only in this paper the model that best agrees with the dielectric response of the insulation system. It is a simple 4-parameter structure $R_m-L-(R_p // (R-C))$ derived from the visual analysis of the current charging/discharging the winding insulation. $R_m = 47\Omega$ is the measurement resistance.

As shown in Fig. 5, this model structure explains the shape of the measured current i_m as the sum of two currents i_p and i_c . The function f and g of the state-space representation (1) are obtained considering the capacitance voltages and the inductance currents as state variables.

Fig 6 shows the good agreement between the measured and simulated currents for the estimated parameters of proposed model. Table I gives the parameter means and standard deviations for ten experimental records for each T°C.

In Fig. 7, we present the relative evolution of the estimated parameters (θ/θ_0) according to temperature changes, where θ_0 is the estimated parameter at ambient temperature (30°C). The identified resistance is still almost constant for all temperatures; this should be explained by the fact that we keep always the same excitation frequency provided by the pulses generator, then the skin effect remains the same and keeps resistance unchanged. Nevertheless, this evolution is clearly not consistent with the temperature dependency of the copper resistance. This tends to prove that the R lumped element of the model structure does not deal with a physical resistance. Furthermore, a net increase is noticed for the capacitance with the increase of test temperature. At 160°C, it is about 8% higher than its initial value. This evolution is of course due principally to temperature increase and not to insulation aging. Actually, since the insulation capacitance is a critical part that could define the winding insulation end of life [11], this important information should be taken into account in establishing a monitoring protocol with the ability to distinguish between insulation aging and temperature variations.

V. CONCLUSION

Operational conditions such as temperature, frequency and moisture affect the dielectric response of electrical generators insulation system. We have proposed in this study to investigate the short effect of temperature changes on estimated parameters of diagnostic model. It appears that the insulation resistance and inductance of a simple lumped model structures are not considerably affected by temperature variation, while insulation capacitance is clearly increased, comparing to its initial value, with the increase of temperature, this result is consistent with other results shown in section III. The utility of this information is to take into account the capacity evolution due to temperature variation, and propose diagnosis models able to make the difference between this evolution and evolution due to insulation degradation. It should be noted that we realize in parallel, experiments of accelerated aging on

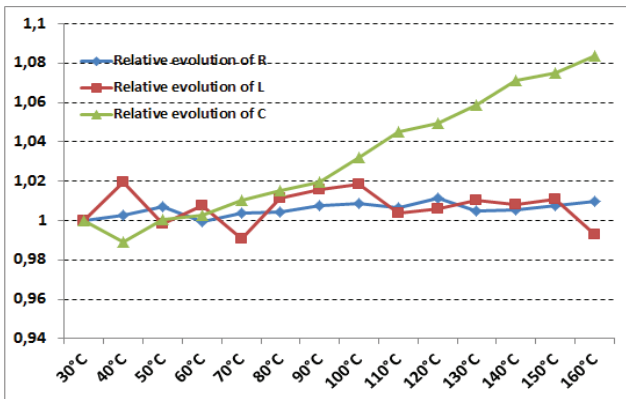


Fig. 7. Parameters evolution according to temperature variations

stator winding insulation and results should be compared to results presented in this study to take into account aging and short time temperature changes effect on dielectric response of insulation. The aim is to propose better knowledge diagnostic models. We note also that simple behavior models are used here, however, an extensive study with more complex knowledge based models is recommended for further work, to propose diagnostic models with diagnosis indicator only related to the insulation aging.

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