



HAL
open science

Predictive diagnostic based on HF modeling of electrical machines windings

Mustapha Toudji, Stéphane Duchesne, Guillaume Parent

► **To cite this version:**

Mustapha Toudji, Stéphane Duchesne, Guillaume Parent. Predictive diagnostic based on HF modeling of electrical machines windings. IEEE International Electric Machines and Drives Conference (IEMDC), May 2019, San Diego, United States. pp.901–906, 10.1109/IEMDC.2019.8785322 . hal-04114197

HAL Id: hal-04114197

<https://hal.science/hal-04114197>

Submitted on 5 Jun 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Predictive diagnostic based on HF modeling of electrical machines windings

Mustapha Toudji, Stéphane Duchesne and Guillaume Parent

Univ. Artois, EA 4025, Laboratoire Systèmes Électrotechniques et Environnement (LSEE), F-62400 Béthune, France

Abstract—Early aging of electrical machines is most commonly due to Electrical Insulation System (EIS) faults. Depending on the applications the electrical machine is used for, the EIS is subject to different stress factors, such as thermal, mechanical and electrical stresses, which can lead to a progressive deterioration of the organic materials it is made of, especially in terms of insulative properties. The aim of this paper is to show that it is possible to anticipate the change of those insulative properties in order to implement it in a predictive diagnostic tool allowing to highlight the parameters which are the best to monitor while the electrical machine is running under normal operation conditions.

Index Terms—Electrical insulation system, aging, predictive diagnostic

I. INTRODUCTION

Electrical machines health monitoring is a major issue in order to insure continuity of service in industrial processes. Possible failures can have several origins. Among them, the ones related to an Electrical Insulation System (EIS) fault are the most commonly encountered [1]–[5]. Indeed, the EIS is usually composed of organic materials that are very sensitive to electrical stresses generated by the electrical drive supplying the machine, which may cause a considerable reduction in the service life of the latter. For this reason, it is essential to develop efficient tools allowing to monitor the health condition of the EIS in order to be able to anticipate the electrical machines failures with a high level of accuracy. Previous studies highlighted that it is possible to monitor the health condition of the EIS by analyzing the resonance frequency variations of the electrical machine windings [6]–[8]. Nevertheless, the main limitation of this method is its calibration step since measurements are required, making it impossible to use at the design step of the electrical machine. On the other hand, other works [9] showed that it is possible to accurately model *a priori* an electrical winding in a predetermined frequency band using an RLC lumped parameter equivalent circuit that allows to describe all phenomena occurring in it.

The aim of this paper is to show that combining the two aforementioned approaches to perform HF modeling of electrical windings allows to build a predictive monitoring tool dedicated to the EIS.

This work has been achieved within the framework of CE2I project (Convertisseur d’Energie Intégré Intelligent). CE2I is co-financed by European Union with the financial support of European Regional Development Fund (ERDF), French State and the French Region of Hauts-de-France.

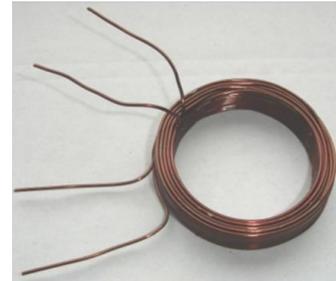


Fig. 1. 25-turn round coil [8]

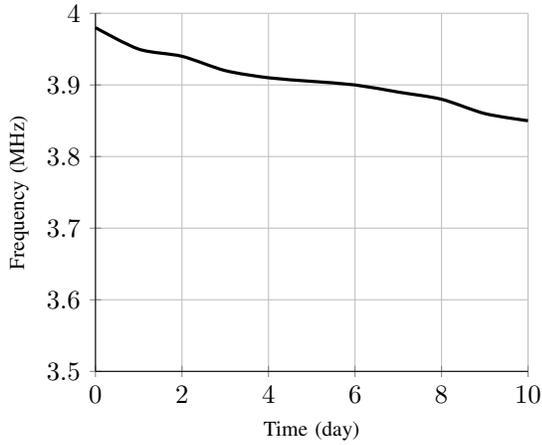
II. AGING OF THE EIS

A. Indicators of aging

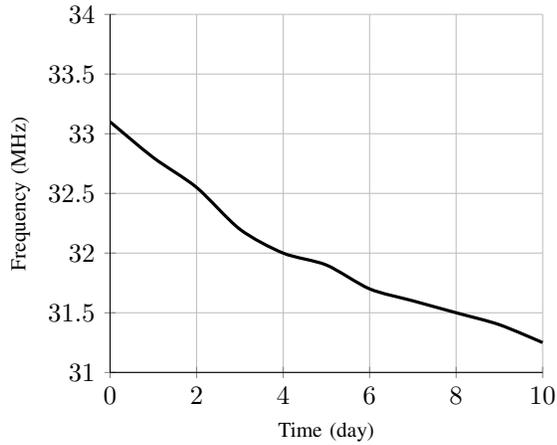
An insulating material subject to aging loses its insulating properties in a progressive and irreversible way. The main consequence of this alteration is a slow decrease of the Partial Discharge Inception Voltage (PDIV), which leads to partial discharge appearance, and thus leads to end-of-life for the majority of machines [5]. This is a vicious cycle. Since an electrical machine aging and its EIS aging are both directly connected [4,10], it is possible to monitor the health of the machine by monitoring the health of the EIS. Several approaches can be found in the literature [11,12], each one using a specific indicator of aging:

- insulation resistance measurement and/or polarization index [2,13,14] ;
- partial discharge monitoring [15]–[18] ;
- HF behavior of the electrical machine monitoring [6]–[8,19].

The study presented in this paper is based on the latter approach. Previous works [7,8] showed that EIS aging of a winding leads to a significant variation of both its resonance frequency, denoted Δf_r . As an illustration, Fig. 2 presents the variation of both the parallel and series resonance frequencies, i.e. 1st and 2nd resonance frequencies, denoted $f_{r\text{para}}$ and $f_{r\text{series}}$, of a round coil made of 0.95 mm diameter classic magnet wire enameled with 200 °C thermal class insulating material during an accelerated aging under 280 °C. The coil has a diameter of 40 mm and is made of 25 turns (5 layers and 5 turns per layer) (Fig. 1). The most relevant information that can be drawn from Fig. 2 is that the values of Δf_r are measurable. Then, monitoring the health of the EIS of the winding of an electrical machine is possible. This method is relatively easy to implement, even with electrical machines in running condition.



(a) Variation of parallel resonance frequency



(b) Variation of series resonance frequency

Fig. 2. Variation of the resonance frequencies of a 25-turns round coil with respect to aging time for a global aging

Nevertheless, the resonance frequencies of a winding, denoted f_r , depend on several parameters, such as its geometry (wire dimensions, number of turns, location inside the machine...) as well as the material it is made of (conducting and insulating material). In consequence, monitoring Δf_r would require to monitor a broad frequency band, which is a difficult and expensive task to do. Hence, to overcome this drawback, it would be very useful to evaluate the frequency band to monitor *a priori*. Unfortunately, as previously mentioned, since f_r depend on so many parameters, they are to be determined for each winding, i.e. for each machine. For this reason, they are impossible to be evaluated *a priori*. The same works [7,8] also highlighted that EIS aging of a winding leads to a significant variation of its turn-to-turn capacitance, denoted ΔC_t (Fig. 3). This observation remains true, even if there is an insulation varnish between the wire [20].

A major outcome of those studies is that ΔC_t is not dependent on the geometry of the windings nor the geometry of the electrical machine. Actually, ΔC_t only depends on the permittivity and the thickness of the insulating layer

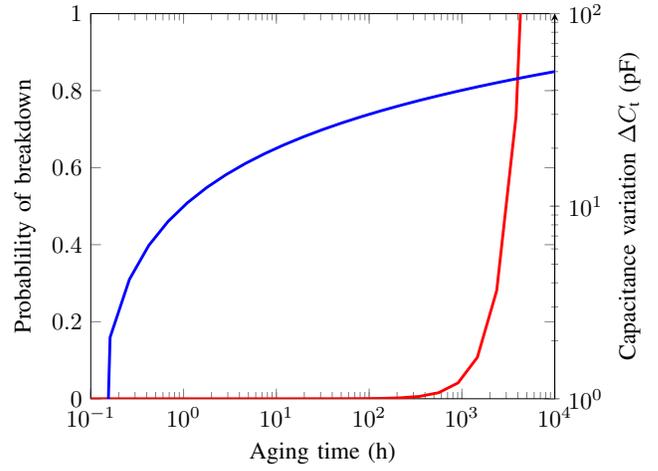


Fig. 3. Correlation between the probability of breakdown of the EIS of a pair of twisted wires [21] (in red) and its capacitance variations (in blue) as functions of time

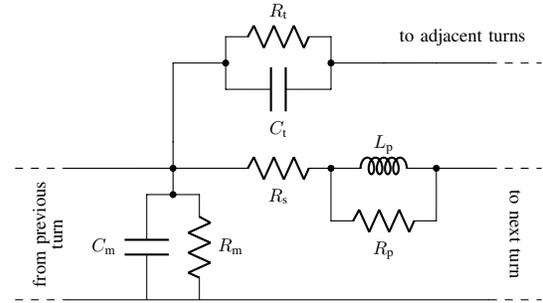


Fig. 4. Lumped parameter equivalent circuit of one turn.

composing the EIS. Based on this observation, for a given wire, it is possible to establish abacuses of ΔC_t as a function of aging time from simple test devices, such as standardized pairs of twisted wires [21] for example, and use those abacuses:

- to compute *a priori* the values of Δf_r thanks to an equivalent lumped parameter circuit [9,22];
- to establish a relation between the variations of the resonance frequencies and the variations of turn-to-turn capacitances.
- to determine critical values of ΔC with regard of the remaining lifetime of the EIS

B. RLC model of a winding

For each turn of a winding, a lumped parameter equivalent circuit (Fig. 4) can be established. It includes the turn resistance R_s , representing the Joule losses, the self-inductance L_p , the turn-to-turn capacitance C_t , the turn-to-ground capacitance C_m and the turn-to-turn and turn-to-ground dielectric losses resistances R_t and R_m respectively. Moreover, in presence of an iron core, the core losses are taken into account through R_p . The equivalent circuit for a complete winding can be obtained by reproducing the elementary cell presented in Fig. 4 as many times as the number of turns in it and by connecting them

depending on the topology of the considered winding. All those parameters can be determined by means of finite element analysis (FEA), as detailed in [9]. This approach offers two advantages. The first one is that all aforementioned parameters can be determined *a priori*, which means it can be used at the design step. The second one is that it allows for considering lumped parameter values specific to each turn, which could not be done from measurements. Once the model of the winding is built, it can be used to determinate the response of the winding both in time and frequency domains [9].

C. Determining the variation of turn-to-turn capacitances by means of accelerated aging procedure

The presented study focuses on industrial machines connected to a conventional electrical network. That means that the machines are supplied by a purely sinusoidal voltage at 50 Hz or 60 Hz. In this case, the aging of the windings is mainly due to thermal stress [10,12].

The IEC 60851 [21] thermal class of the insulation layer of the studied wire is 200 °C. The accelerated thermal aging procedure was applied to pairs of twisted wires under 240 °C and 280 °C during 10, 35 and 70 days. As an example, an aging under 240 °C for 70 days to a regular aging 12 000 h at a temperature of 200 °C, which is an usual running temperature in electrical machines [23]. During the accelerated aging process, the values of ΔC were reported (Fig. 5).

D. Aging simulation procedure

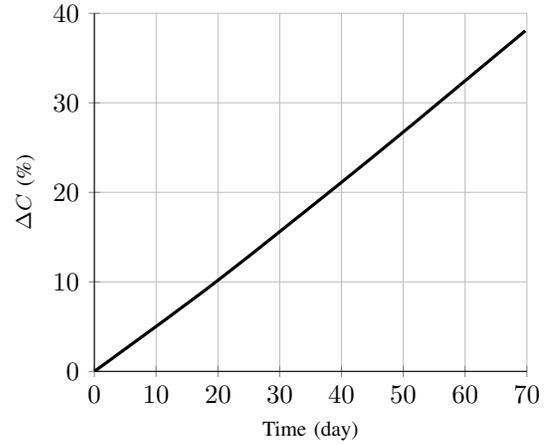
The aging simulation procedure allowing to determine the values of Δf_r is presented in Fig. 6. In a first time, the RLC model of the healthy considered winding is built according to the procedure detailed in Section II-B. Then, it is solved using Kirchhoff's laws to obtain the response of the winding in frequency domain, and thus obtain its resonance frequencies which be later used as references. In a second time, the procedure is repeated using modified values of C_t , which come from aging tests detailed in Section II-C, depending on the operating time to be considered. Solving the RLC model using modified C_t leads to modified values of f_r . A correspondence between ΔC_t and Δf_r is obtained, and thus a correspondence between the aging time and Δf_r . The obtained abacus can then be used in order to monitor the health of the EIS of the winding.

The strength of the proposed method lies in its flexibility. Indeed, it is possible to modify the value C_t of one, several or all of the turns in the winding. This way it is possible to evaluate Δf_r related to the aging of a specific turn or group of turns.

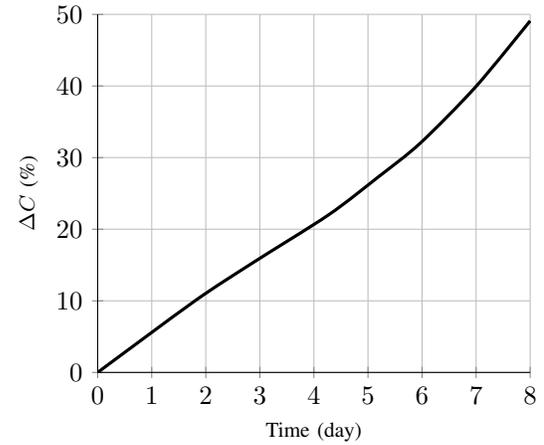
III. RESULTS

A. Studied coil

As an example of application, a coil composed of 34 turns made of enameled flat wire is studied (Fig. 8). The wire is 2 mm height and 5 mm width.



(a) At 240 °C



(b) At 280 °C

Fig. 5. Variation of ΔC of pairs of twisted wires with respect to aging time

B. Global aging

In this part, a global aging of the winding is considered, which means that all the turn-to-turn capacitances C_t in the model are modified.

The simulation results are presented in Fig. 7. It clearly shows the influence of the aging on both the parallel and series frequencies. This influence is significant as soon as day 10 on both resonance frequencies and the total variations of $f_{r_{para}}$ and $f_{r_{series}}$ are equal to 2.75 MHz and 78.57 kHz respectively, which are values that actually are measurable.

C. Local aging

As previously mentioned, the model of Fig. 4 allows to modify as many C_t as the user wants. It is then possible to focus on one C_t . Fig. 10 presents the variations of $f_{r_{para}}$ and $f_{r_{series}}$ when either $C_{t_{1-2}}$ and $C_{t_{9-26}}$ are modified, which correspond to turns located at the beginning and the middle of the winding. The aging was realized under 280 °C for 8 days. Two main conclusions can be drawn from Fig. 10. The first one is that the variation of a single C_t has an impact on both $f_{r_{para}}$ and $f_{r_{series}}$ whatever its location in the winding. The

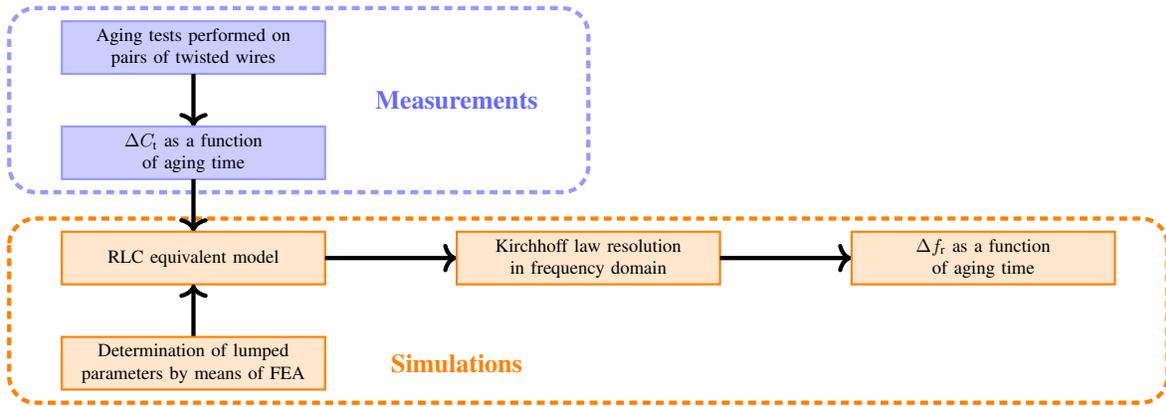


Fig. 6. Simulation procedure for the determination of Δf_r

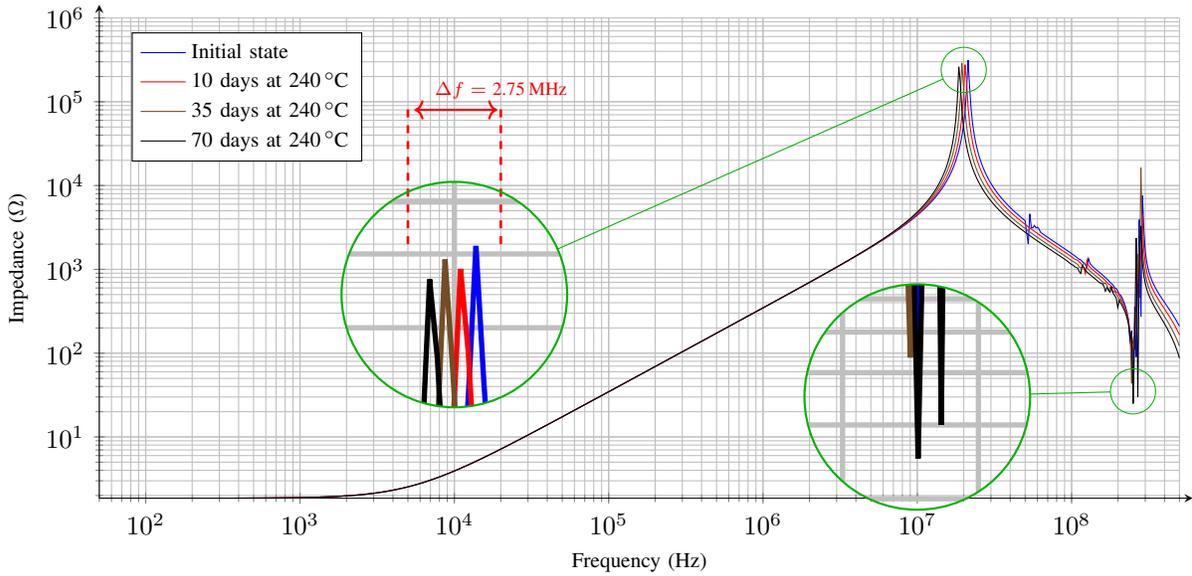


Fig. 7. Variation of the frequency response of the studied winding under different aging times

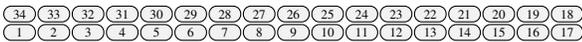
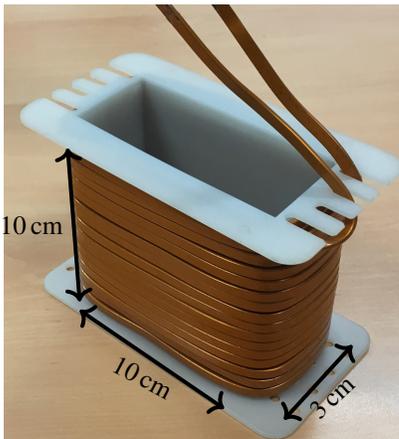
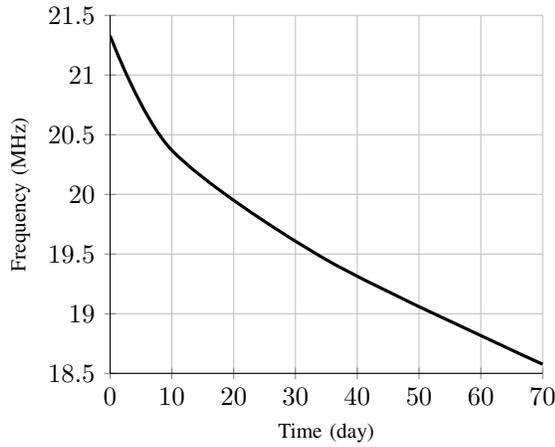


Fig. 8. Studied coil

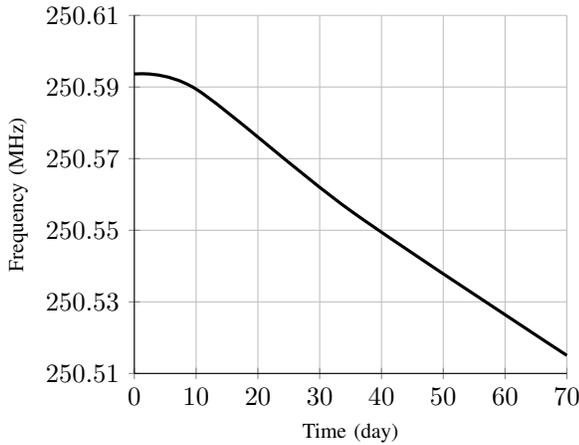
second conclusion is that, as with the global aging, the Δf_r induced variations are measurable.

D. Comparison between the two coils

Fig. 11 shows a comparison between the relative variation of the parallel resonance frequency $\Delta f_{r\text{para}}$ with respect to aging time for a global aging of the 25-turn coil (Fig. 1) and the 34-turn coil (Fig. 8). They are of different geometries in terms of size and wire shape. The only parameter they share is their EIS, which is made of the same material. This is made on purpose. Indeed, Fig. 11 shows that despite the significant differences between the two coils, the variations of $\Delta f_{r\text{para}}$ follow a similar pattern as well a similar order of magnitude. This comparison tends to support the fact that the variations of $\Delta f_{r\text{para}}$ do not depend on geometric parameters, but only depend on the variations of ΔC_t .



(a) Variation of parallel resonance frequency f_{rpara}



(b) Variation of series resonance frequency $f_{rseries}$

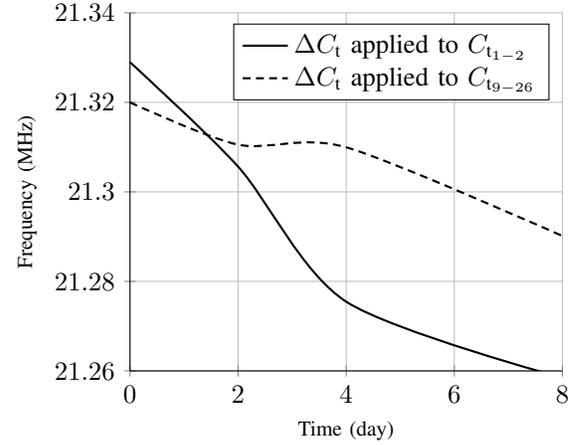
Fig. 9. Variation of the resonance frequencies with respect to aging time for a global aging

IV. DISCUSSION AND FUTUR WORKS

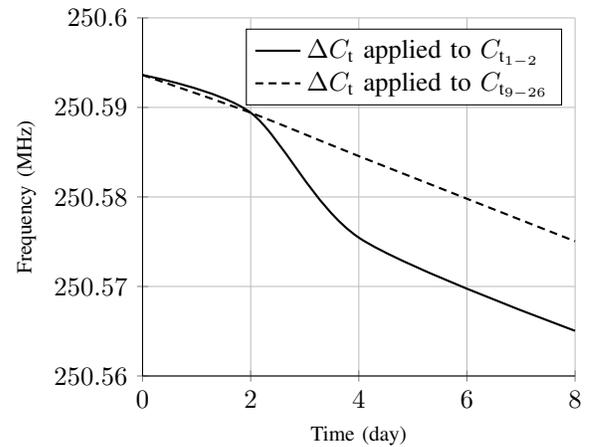
On one hand, the lumped parameter equivalent circuit of Fig. 4 is able to precisely quantify a variation of the resonance frequencies resulting from a variation of one or several turn-to-turn capacitances of a coil. On the other hand, the variations of those capacitances can be obtained by mean of accelerated thermal aging and can be extrapolated to a regular thermal aging according to Arrhenius' equations [24]

The method is well suited to thermal aging since the relationship between accelerated thermal aging and regular aging through by means of variation of capacitances is very well documented in the literature. As of now, it limits the spectrum of application to global thermal aging windings of electrical machines directly connected to conventional grids.

The study of local aging due to electrical issues, such as partial discharge in windings of machines supplied by power electronic converters, following the same approach is feasible but way more complicated. Actually, it's been shown that establishing variations of resonance frequencies by modifying one capacitance only in the lumped parameter circuit is possi-



(a) Variation of parallel resonance frequency f_{rpara}



(b) Variation of series resonance frequency $f_{rseries}$

Fig. 10. Variation of the resonance frequencies with respect to aging time for a local aging

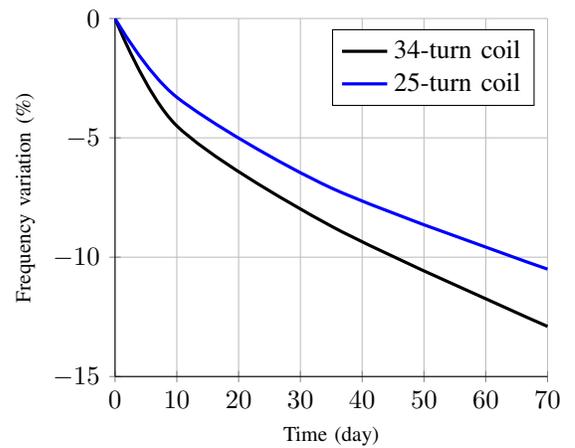


Fig. 11. Relative variation of the parallel resonance frequency Δf_{rpara} with respect to aging time for a global aging - comparison between the 25-turn coil (Fig. 1) and the 34-turn coil (Fig. 8).

ble. But the problem lies in the experimental determination of ΔC , which should be done by means of electrical aging in order to be representative.

V. CONCLUSION

This study showed the ability of a HF model to determine the most relevant frequencies for monitoring the health status of winding insulation. The fluctuations in first parallel and series resonance frequencies have been correlated with the alteration of the state of the insulation layers of the enamel conductors. The computation is based on the capacitance variations measured during a measurement campaign under thermal aging. Two cases were examined to check the approach. The first one describes a slow aging of the whole EIS and allows to establish *a priori* the frequency bandwidth to be monitored. In a second case, more sporadic faults were implemented. This validated the sensitivity of the method and revealed that local faults affect the same resonance frequencies in a measurable way.

Thanks to this method, it will be possible to correlate more precisely the aging of a winding and the fluctuations in resonance frequencies in order to define stopping criteria allowing curative maintenance.

REFERENCES

- [1] W. Thomson and M. Fenger, "Current signature analysis to detect induction motor faults," *IEEE Industry Applications Magazine*, vol. 7, no. 4, pp. 26–34, Jul. 2001.
- [2] G. C. Stone, E. A. Boulter, I. Culbert, and H. Dhirani, *Electrical insulation for rotating machines: design, evaluation, aging, testing, and repair*. John Wiley & Sons, 2004, vol. 21.
- [3] M. Riera-Guasp, J. A. Antonino-Daviu, and G.-A. Capolino, "Advances in Electrical Machine, Power Electronic, and Drive Condition Monitoring and Fault Detection: State of the Art," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 3, pp. 1746–1759, Mar. 2015.
- [4] V. Madonna, P. Giangrande, L. Lusuardi, A. Cavallini, and M. Galea, "Impact of thermal overload on the insulation aging in short duty cycle motors for aerospace," in *2018 IEEE International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles & International Transportation Electrification Conference (ESARS-ITEC)*, Nov. 2018, pp. 1–6.
- [5] G. C. Montanari and P. Seri, "Investigating Aging Phenomenology of Type I and Type II Insulation Systems of Rotating Machines Fed by Power Converters," *IEEE Transactions on Fundamentals and Materials*, vol. 139, no. 2, pp. 47–53, Feb. 2019.
- [6] P. Werynski, D. Roger, R. Corton, and J.-F. Brudny, "On-line monitoring of insulation aging in ac motors fed by pwm inverters," in *IEEE International Conference on Electrical Machines and Drives (IEMDC)*, May 2005, pp. 1942–1948.
- [7] F. Perisse, P. Werynski, and D. Roger, "A New Method for AC Machine Turn Insulation Diagnostic Based on High Frequency Resonances," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 14, no. 5, pp. 1308–1315, Oct. 2007.
- [8] S. Savin, "Nouvel indicateur de vieillissement de l'isolation interspires des machines électriques utilisées en aéronautique," Ph.D. dissertation, Université d'Artois, 2013.
- [9] M. Toudji, G. Parent, S. Duchesne, and P. Dular, "Determination of winding lumped parameter equivalent circuit by means of finite element method," *IEEE Transactions on Magnetics*, vol. 53, no. 6, pp. 1–4, Jun. 2017.
- [10] B. Jokanović, M. Bebić, and N. Kartalović, "The influence of combined strain and constructive solutions for stator insulation of rotating electrical machines on duration of their reliable exploitation," *International Journal of Electrical Power & Energy Systems*, vol. 110, pp. 36–47, Sep. 2019.
- [11] G. Stone, "Recent Important Changes in IEEE Motor and Generator Winding Insulation Diagnostic Testing Standards," *IEEE Transactions on Industry Applications*, vol. 41, no. 1, pp. 91–100, Jan. 2005.
- [12] A. Cimino, F. Jenau, C. Staubach, A. Mashkin, and F. Pohlmann, "Analysis of fault detection in the electrical insulation system of rotating machines," in *International Conference on Diagnostics in Electrical Engineering (DIAGNOSTIKA)*, Sep. 2018, pp. 1–4.
- [13] D. Schump, "Testing to assure reliable operation of electric motors," in *37th Annual Conference on Petroleum and Chemical Industry*, 1990, pp. 179–184. [Online]. Available: <http://ieeexplore.ieee.org/document/218099/>
- [14] "IEEE Recommended Practice for Testing Insulation Resistance of Electric Machinery," *IEEE Std 43-2013 (Revision of IEEE Std 43-2000)*, pp. 1–37, Mar. 2014.
- [15] G. Stone, H. Sedding, and M. Costello, "Application of partial discharge testing to motor and generator stator winding maintenance," *IEEE Transactions on Industry Applications*, vol. 32, no. 2, pp. 459–464, 1996.
- [16] R. Bartnikas, "Partial discharges. Their mechanism, detection and measurement," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 9, no. 5, pp. 763–808, Oct. 2002.
- [17] A. Cavallini, A. Contin, G. Montanari, and F. Puletti, "Advanced PD inference in on-field measurements. part 1: Noise rejection," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 10, no. 2, pp. 216–224, Apr. 2003.
- [18] A. Cavallini, M. Conti, A. Contin, and G. Montanari, "Advanced PD inference in on-field measurements. part 2: identification of defects in solid insulation systems," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 10, no. 3, pp. 528–538, Jun. 2003.
- [19] P. Nussbaumer, M. A. Vogelsberger, and T. M. Wolbank, "Exploitation of induction machine's high-frequency behavior for online insulation monitoring," in *IEEE International Symposium on Diagnostics for Electric Machines, Power Electronics and Drives (SDEMPED)*, Aug. 2013, pp. 579–585.
- [20] L. Fetouhi, D. Malec, P. Manfe, and J. Martinez-Vega, "Experimental Study on the Evolution of Dielectric Properties of Impregnating Varnishes with Thermal Aging," in *Annual Report - Conference on Electrical Insulation and Dielectric Phenomena (CEIDP)*, Oct. 2018, pp. 618–621.
- [21] "IEC60851-5: Winding wires - Test methods - Part 5: Electrical properties," International Electrotechnical Commission, Standard, 2008.
- [22] B. Mirafzal, G. L. Skibinski, and R. M. Tallam, "Determination of Parameters in the Universal Induction Motor Model," *IEEE Transactions on Industry Applications*, vol. 45, no. 1, pp. 142–151, 2009.
- [23] "IEC60505: Evaluation and qualification of electrical insulation systems," International Electrotechnical Commission, Standard, 2011.
- [24] "IEC 60216-3: Electrical insulating materials - Thermal endurance properties - Part 3: Instructions for calculating thermal endurance characteristics," International Electrotechnical Commission, Tech. Rep., 2006.