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Walid BOUGHANMI[1, 2], **Daniel ROGER**[1, 2]

Univ. Lille Nord de France, F-59000 Lille, France (1), UArtois, LSEE, F-62400 Béthune (2)

Detection of high frequency magnetic signature for large electrical machines: a monitoring tool

***Abstract**. The turn-to-turn insulation quality of electrical machines can be monitored using high frequency resonance detection in windings. Indeed, for standard turn insulation made of polyester-imide and polyamide-imide coating, the polymer aging causes a slight increase of the turn-to-turn capacitance therefore a slight change of several winding resonance frequencies. Such change can be detected by an appropriate monitoring system. For large machines, the interesting spectrum is in the range 10MHz -50MHz. The paper describes a method based on magnetic field measurements able to detect such resonance frequencies for large machines.*

***Streszczenie.** Jakość izolacji wokół cewek maszyn elektrycznych może być monitorowana stosując metodę detekcji rezonansem wysokoczęstotliwościowym. Rzeczywiście, dla standardowej izolacji zwoju wykonanej z poliestroamidu i pokrytego poliamidowa powłoką, starzenie powoduje niewielki wzrost pojemności miedzyzwojowej dla różnych częstotliwości rezonansowych. Taka zmiana może być wykryta za pomocą odpowiedniego systemu monitoringu. W przypadku dużych maszyn, ciekawe spektrum występuje w zakresie 10MHz-50MHz. W artykule opisano metodę opartą na pomiarach pola magnetycznego dla dużych maszyn. (**Detekcja pola magnetycznego wysokiej częstotliwości w dużych maszynach elektrycznych: narzędzie monitorowania**)*

Keywords: electrical machine – winding insulation – HF resonance – magnetic field sensor.
Słowa kluczowe: maszyna elektryczna, izolacja uzwojeń, rezonans wysokoczęstotliwościowy, sensor pola magnetycznego.

Introduction

Large electrical machines are critical resources for many industrial applications. They are the object of predictive maintenance programs along their life. The prediction of damages that may occur in the winding insulation is an important part of the process. Monitoring of insulation system is a very old problem that has existed since the appearance of electrical generators. The characterization of the ground insulation quality is the subject of several standards that results of earlier studies [1]. However, the quality of insulation between turns is more difficult to verify, the existing method consists of connecting a capacitor previously charged at high voltage to a phase of the machine under tests and comparing the transient discharge for the 3 phases [2].

Earlier information can be obtained by analyzing the high frequency behaviour of operating machine windings, in order to detect a slight variation of resonance frequencies corresponding to the turn insulation aging [3, 4]. The proposed paper shows that such measurements are possible using magnetic field in the existing gap between the magnetic core and the machine frame (construction cooling gap) when the windings are fed with the appropriate injection system.

The good detection and quantification of the Partial Discharge which induces a HF local current will be achievable by measuring local magnetic field instead of global current [5]. Thus, the aim of the paper is to open new possibilities for monitoring the turn-to-turn insulation quality of large machines using sensors in an unusual place free of any electric field.

HF impedance measurement of the elementary coil for the large electrical machine

The experimental approach needs an identification of the winding. A measure of the coil impedance over a wide frequency band 10MHz–50 MHz is made by an impedance analyzer type 4249A AGILENT [6]. It is an effective solution for impedance measurement and analysis of components and circuits, it works using the well known 4-point method. Given the large size of the system that we handle (an eight poles - 135 kilowatts), it is essential to use a calibrated connection system between the analyzer and the machine. This configuration of measurement using four identical coaxial cables of good quality can solve the problem of remote measurement [7].

The impedance analyzer and its calibrated connection system are used for impedance measurements of an elementary coil section (Fig.1) of the 135 kW machine. In order to start the operations on this machine, the elementary coil was identified with labels and the external connections for this coil were removed in order to eliminate the parasitic influence of the external circuit.

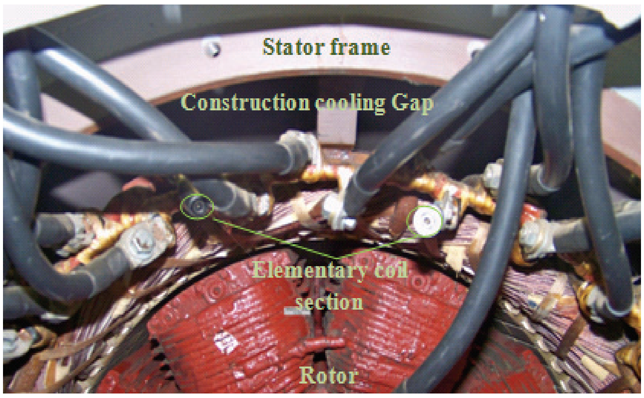

Fig. 1. Synchronous machine (8 poles, 135 KW)

Fig. 2 shows the variation of the impedance modulus of the elementary coil versus frequency; several resonances can be observed: two maximums and one minimum.

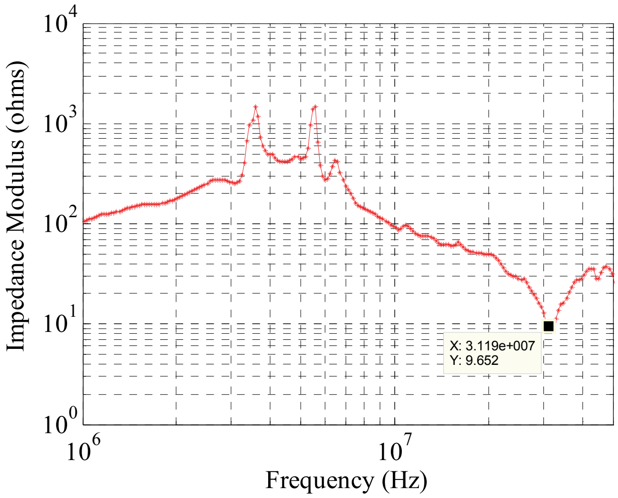

Fig. 2. Impedance modulus versus frequency

In Fig. 2, the minimum of the modulus corresponds to a series resonance and a maximum of the current magnitude when a HF voltage generator feeds the coil; consequently, this resonance will be easier to detect using magnetic field measurements. This series resonance appears at 31.19MHz with a modulus slightly under 10Ω, it corresponds to a relatively large HF current when the coil is fed with the appropriate injection system.

Measurement of the HF magnetic field emitted from the elementary coil section

Large electrical machines are built with a steel frame that supports the stator-laminated core, leaving a cooling gap between the laminated stator and the frame. The presence of this gap can be used to add small magnetic sensors in order to measure the high frequency signature of the machine. Fig. 1 illustrates the experimental machine available in the laboratory. The excitation of the coil is fed by a sine generator at the resonance frequency; so we can measure the magnetic field in the cooling gap between the magnetic core and the stator frame with an adapted sensor previously calibrated; Fig. 3 is a schematic presentation of the experimental machine cross section; which shows the excited coils and the position of the sensor.

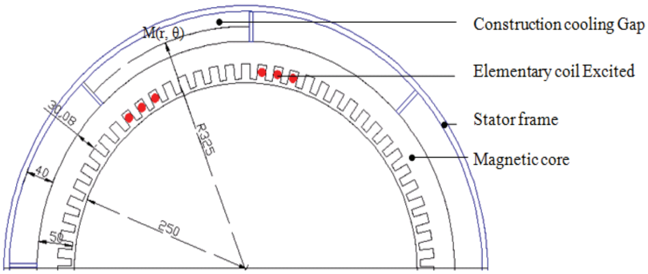

Fig. 3. Schematic overview of the machine

The considered machine coil is placed in 6 slots; the angular distance between two consecutive slots is 2.5°. The magnetic circuit has an inside diameter of 50 cm and a length of 38 cm. Its thickness is 5 cm. The positions of measurement points of magnetic field are given by the polar coordinates (r, θ). The sensor moves on the line drawn in the cooling gap. The field measured in the cooling gap represents the contribution of all conductors in the six slots.

The magnetic sensor is the well-known plat coil; the transfer function V=f(B) results from the fundamental faraday's law of induction [9].

$$V = -n\frac{d\Phi}{dt} = -n \times A\frac{dB}{dt} = -\mu_0 \times n \times A\frac{dH}{dt} \tag{1}$$

where: Φ – magnetic flux, A – section of coil, n – number of turns.

The sensor is presented in Fig. 4, the standard plat coil associated to a low-noise amplifier fed by batteries. The sensor is designed to operate at between 1MHz and 50MHz, according to the resonance frequency of the machine coil. The sensitivity S=V/H [mV/A.m] at constant frequency (f=31MHz) of air coil sensor can be calculated as shown in equation (2):

$$S = 2\times10^{-7}\pi^2 f \times n \times (l_e + l_i)(L_e + L_i) \tag{2}$$

where: L_i / L_e are inside / outside length of the plat coil, l_i / l_e, the inside / outside width and f , the source frequency.

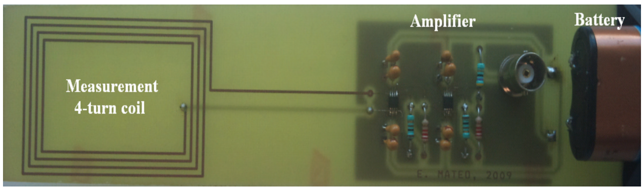

Fig. 1. Magnetic field sensor

Results of HF magnetic field: To measure the normal component H_n (r, θ) of the external magnetic field emitted by the elementary coil of the 135 KW machine, the coil sensor is placed in the construction cooling gap parallel to the stator core; its position is defined by the point M (r=32cm, θ=20°, z=15 cm) as shown in the Fig. 3. The conductors in the slots are excited by a sinusoidal high frequency with a function generator (50Ω, 50MHz) and a power amplifier (1-80MHz) well calibrated. The connections are provided by 50 ohms coaxial cables. Fig. 5 shows the measurement device.

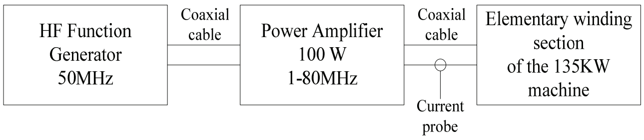

Fig. 5. Schematic diagram of HF injection system

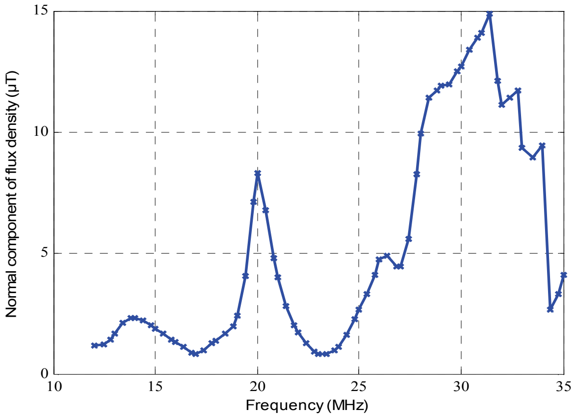

Fig. 6 The normal component of flux density as a function of frequency

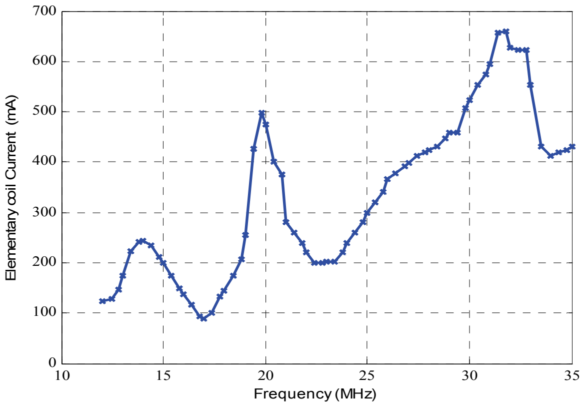

Fig. 7. The elementary coil current as a function of frequency

Fig. 6 and Fig. 7 show respectively the variation of the modulus of flux density normal component B_n and the elementary coil current versus frequency. The flux density is maximum at the series resonance frequency where the current is also maximum (31 MHz-650 mA).

The minimum impedance at 31 MHz, previously found using the impedance analyzer, is confirmed by scanning the frequency range. Another resonance frequency appears at 20 MHz, its due of the interaction the coil with connections cables. These results show that the magnetic field measured in the cooling gap is representative of HF phenomena located in the coil hosted in the slots.

Interpretation

For electrical machines, the current passing through the stator coil produces a magnetic field ($\vec{H}_0$) and magnetic flux density ($\vec{B}$) in the magnetic core. The phenomena can be classified according to frequency. At low frequency, when the skin thickness δ is greater than or equal to half the thickness of a magnetic sheet, the influence of induced currents on the distribution of the magnetic field remains low, the magnetic field is uniform within each sheet. The magnetic core achieves its traditional role, which is to concentrate the field lines toward the air gap in order to perform the classical electromechanical conversion. The case of high frequencies is quite different. When the skin thickness δ is small compared to the sheet thickness *a*, the magnetic field does not penetrate inside the magnetic sheets, it stays in a very small thickness under the surface of each sheet [10]; therefore, the magnetic field is concentrated in the insulation layer between sheets and in the skin depth of each sheet. Fig. 8 illustrates the cross-section view of the stator magnetic circuit, which represents the induced current associated with the phenomenon of diffusion of the field in each sheet; the small arrows indicate the direction of the induced current density.

It appears the question: what explains the presence of the HF magnetic field in the cooling gap of the machine? In fact, the eddy currents cause a reaction; they create a field that opposes the excitation field. This reaction removes the field in the middle of each sheet on an area whose width depends on the frequency. The magnetic field and eddy currents exist only in a thin layer beneath the surface of each sheet. Eddy currents are naturally close at the end of each magnetic sheet. The outer surface of the stator at *y=b* on Fig 8. is a stack of thin sheets where eddy currents flow from one side or each sheet toward the other side. Considering that the insulating layer between the magnetic sheets much thinner that its thickness and for low skin depth, it is possible to see the external surface of the sheet stack as a layer of eddy currents circulating beneath the outer surface of the magnetic core. This current layer has a decisive influence on the external magnetic field. The theoretical results of [10] show that the induced current loops act as elements of transmission of information from HF currents in windings outwards the outside of the laminated core: they acts as transmission belts for HF phenomena in windings; the magnetic laminated core becomes transparent for HF fields.

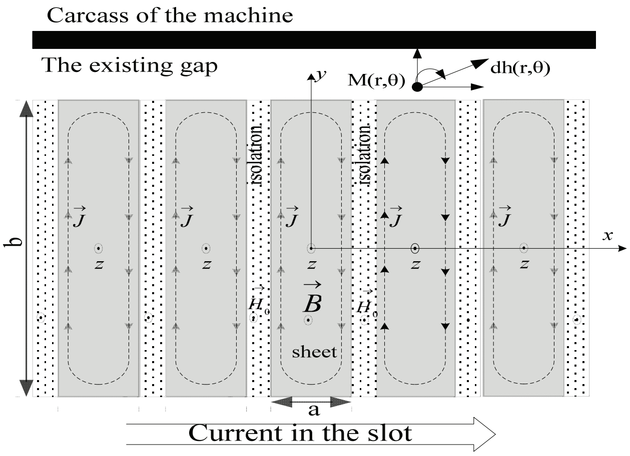

Fig. 8. Distribution of the magnetic field in the electrical sheet

A simulation was made to compute the variation of magnetic flux density into the cooling gap of the experimental machine when the elementary coil emphasized in Fig. 3 is excited by a signal corresponding to the series resonance frequency (f=31MHz). The excitation current is 0.6 A; the HF magnetic sensor moves in the cooling gap on the path defined by the dotted line inFig. 3. The simulation uses the principle of the transparency of the sheet stack established in [10] for high frequencies, when the skin depth is much lower than the thickness of magnetic sheets.

For an elementary conductor of the coil, the magnetic field produced by a current (*i*) flowing in this conductor is tangent to a circle, which is centred on the conductor whose radius is called *r*. Its modulus is constant and is equal to:

$$\left|\vec{H}_j\right| = \frac{i}{2\pi r} \tag{3}$$

The contribution of all conductors placed in the six slots, gives a magnetic field in the building gap is the sum of 6 vectors [11], as described in (4).

$$\vec{H} = \sum_{j=1}^{6} \vec{H}_j \quad ; \quad \vec{B} = \mu_0 \times \vec{H} \tag{4}$$

Vector equation (3) and (4) are computed for the same current i=0.6A and results are plotted inFig. 2, which shows the variation of the normal flux density versus sensor displacement in the cooling gap.

This study shows that, for high frequencies, the eddy currents in the laminated stator act effectively as transmission belts for high frequency electromagnetic phenomena in winding. This field contains high frequency information that can be used to detect winding insulation aging if the correct HF excitation is achieved. In fact, during the insulation aging, slight variations of resonance frequencies, due to the turns to turns capacitance increase may be used by a new generation monitoring system.

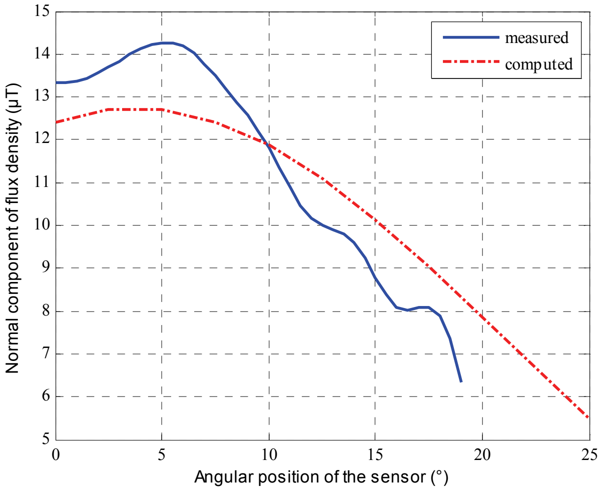

Fig. 2. Normal flux density component versus sensor position

Conclusion

For winding of large electrical machines, resonances located at high frequencies, contain information on the insulation aging. In this paper, authors demonstrate that it is possible to detect these HF resonances by measuring a magnetic flux density in the cooling gap between the magnetic core and the machine frame. In fact, the induction outside a standard laminated magnetic core is representative for the HF phenomena in the coils and it is measurable with a relatively simple HF sensor. The resonance at 31 MHz found in the external field measurements and in the current of elementary coil, has already been detected by direct measurement of the coil impedance. In addition, analytical model of physical phenomena explains the experimental data: the obtained practical and theoretical results are in good concordance. So the HF signature of large electrical machines, determined in this paper opens a new way to control the health of the turn-to-turn insulation of windings and other opportunities such as partial discharge detection and localisation.

Acknowledgments

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Walid Boughanmi (Ph.D Student), University of Artois, LSEE, E-mail: mwalid.boughanmi@gmail.com;
Prof. Daniel ROGER, University of Artois, LSEE, E-mail: daniel.roger@univ-artois.fr. Address: Technoparc Futura, Faculté des Sciences Appliquées 62400 Bethune France.