Prospective Method for Partial Discharge Detection in Large AC Machines using Magnetic Sensors in Low Electric Field Zones

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Abstract **─** The aim of the paper is to present a prospective method for on-line monitoring of partial discharge (PD) in large AC motors. The principle of this system consists to measure the weak high frequency magnetic field, due to PD, in the space between the magnetic core and the external frame of large generators. Special sensor, with a bandwidth adapted to the resonance frequencies of the machine winding, can perform such weak-field measurements. With several sensors, it will be possible to localize PD activities corresponding to insulation weaknesses.

Index Terms **─** Large machine insulation aging, magnetic field sensor, partial discharge monitoring.

I. INTRODUCTION

The insulation systems of large machines which operate at high voltages are made of composite insulating materials that support partial discharges (PD) [1]. These materials are stable over time when the number of PD and their corresponding energy remain within reasonable limits. Many monitoring systems evaluate the overall PD activity for the whole machine insulation system taking information in the machine terminals or connection bars with coupling capacitors or Rogowski coils [2-5]. Other systems use microwave technologies by inserting directional antennas in stator slots; these Stator-Slot-Couplers (SSC) identify whether the PD is originating in the end-winding or in the slot [6-7]. A third family of monitoring systems is based on the detection of mechanical waves (noise specific to PD) [6]. All of these techniques are complementary, they give interesting information on the machine aging; however, the maintenance decisions are still difficult to make. The monitoring of large and expensive machines remains a problem.

The paper proposes a new monitoring method which consists of measuring the low level high frequency magnetic field, created by PD activity, in the cooling gap between the laminated magnetic core and the machine frame.

After a description of the scientific and technological background, a paragraph is devoted to electromagnetic phenomenon in the laminated magnetic core of the machine. It explains how the high-frequency electromagnetic signal is transmitted from the stator bars, in slots, to the free space between the machine laminated core and the frame. Thereafter, the paper is devoted to the experimental demonstration of the ability to implement the new approach on a large machine. The experimental device is built around the stator of the 125MW generator available for research works at the LSEE. Two stator bars are replaced by an experimental line, of similar size, on which a favorable zone to the onset of partial discharges is fitted. A high-frequency equivalent model of the line confirms that the measured signals in the cooling gap circuit are representative of partial discharges created in the stator bar.

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II. SCIENTIFIC AND TECHNOLIGICAL BACKGROUND

The design of large machines has evolved considerably in recent years with the development of simulation tools [7-11]. Their insulation system is made of mineral insulating materials impregnated with resins based on polymers [12]. This technology has proven its reliability despite the inevitable gas vacuoles which remain within the insulation system. When the electric field in a vacuole exceeds a certain threshold, the gas is ionized by a fast electronic avalanche effect; it is the beginning of the partial discharge [13]. Then, the movement of ions and electrons in the gas causes an accumulation of charges on the insulating walls of the vacuole. The direction of motion of the charges is imposed by the electric field vector and the charge accumulation creates an opposite field which shut down the discharge after a few hundred nanoseconds. The electronic avalanche creates a very fast transient in the electrical circuit near the vacuole; the duration of the second phase depends on the response of this external circuit. For a large machine, the external electric circuit corresponds to parallel stator copper bars which form a transmission line for the PD pulse, and the response of such a line creates electromagnetic emissions which can be detected.

For dc voltages, the polarity of the fields and charges does not change, when the internal surfaces of all the vacuoles are charged the PD activity stops naturally. For alternaitve voltages, the charge polarity of the internal walls of each vacuole is reversed at each half-period and the PD global activity does not stops [14].

During each partial discharge the internal surfaces of vacuoles are bombarded by ions and electrons. High energy photons are also emitted. This activity degrades the molecular chains of the polymer while the mineral crystals are more resistant. Therefore, partial discharges cause an erosion of the composite insulation system and tend to increase the volume of vacuoles. The number of partial discharges and the charge quantity displaced tend to increase during the aging of the composite insulation system. These processes are well known, they are at the basis of many monitoring systems of aging of electrical insulation of large machines [1]. Indeed, for a vacuole, the number of partial discharges per period of the voltage and the charge of each of them are two parameters characterizing the vacuole. When these two parameters remain constant over the years, the vacuole is stable. It is obviously impossible to consider separately each vacuole, however, a statistical treatment of the number of PD and their average charge is a good indication of the aging of the whole composite electrical insulation system.

III. HIGH FREQUENCY BEHAVIOR OF LAMINATED CORE

The fast transient phenomena in the windings caused by partial discharges correspond to the upper frequency part of the spectrum, beyond 1MHz. At these frequencies, the eddy currents in the magnetic sheets of the laminated core have a major influence. These currents flow in a very thin layer under the surfaces of each magnetic sheet as shown on Fig. 1, which represents the cross section of the external part of 3 stator sheets.

The eddy current lines, flowing from a side to the other of each magnetic sheet, produce the magnetic field in the cooling gap between the magnetic core and the frame. These current lines are created by high frequency currents in the stator bars, therefore the eddy-current loops act as transmission belts for the information coming from the HF current component in the stator bars.

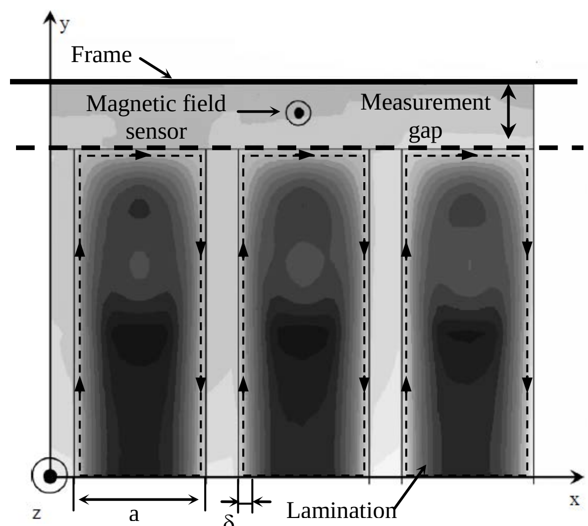

Fig. 1. Simulation of magnetic field and eddy current for large skin depth δ.

Previous studies have demonstrated that, for a skin depth δ much lower than the sheet thickness *a* ($\delta < a/40$), the laminated core can ne considered as transparent for HF phenomena in stator slots [15-

16]. Therefore, when a partial discharge occurs in the isolation between bars, it is possible to detect the resulting fast transient current pulse and quantify the charge by measuring the magnetic field in the cooling gap between the laminated core and the machine frame.

When a partial discharge occurs between two stator bars, a HF current *i* flows in the two bars in opposite directions. The corresponding flux density in the cooling gap can be determined with the Ampere's Law, considering the transparency of the laminated core for such HF phenomena. The magnetic field H consists of two components due to the current in each conductor as describes in Fig. 2 where distances d and e are defined. The resulting magnetic field is weak but it can be estimated by:

$$H = \frac{i}{2\pi(d+e)} - \frac{i}{2\pi d} \quad , \qquad (1)$$

where H is the magnetic field (A/m), i is the partial discharge current (A), e is the distance between the conductors (m) and d the distance between a conductor and the magnetic field sensor (m).

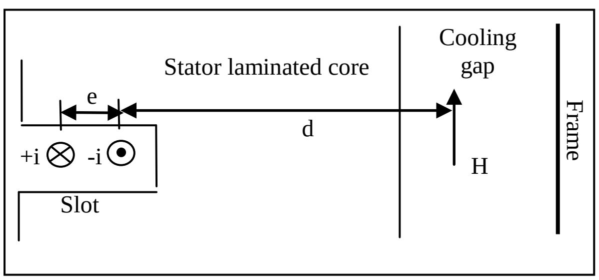

Fig. 2. Magnetic field due to PD between two stator bars.

IV. EXPERIMENTAL VALIDATION

A. Experimental setup

Feasibility of the new PD detection method is tested in the stator of a 125 MW machine (Fig. 3). The stator length is 6.5 m. This machine is used for research, the rotor is removed. A portion of the frame is cut in order to have an access window on the cooling gap, where the magnetic probe is installed.

The stator winding is not powered and two 5 m length cables simulating the HF behavior of stator bars are used. Both cables are spaced at a fixed distance of 2 cm. At the line end, a normalized twisted pair is added to forms a weak point for PD initiation. Once created in the twisted pair, the partial discharge pulse will propagate in the line as it does in the stator bars of a working machine.

To demonstrate the HF behavior of laminated core, the testing protocol is conducted in two parts.

The first measurements are performed outside the stator. The magnetic field probe is placed above the cables, at a distance equal to the width of the stator laminated core (d=65 cm). The position along the cable (1.5 m from the twisted pair) is chosen to coincide with the measurement position of the probe in the free space between the external frame and the stator laminated core (Fig. 4).

The second step of tests consists to put the line and the twisted pair inside the stator (Fig. 3). In this case the magnetic probe is placed in the cooling gap using the window made in the frame.

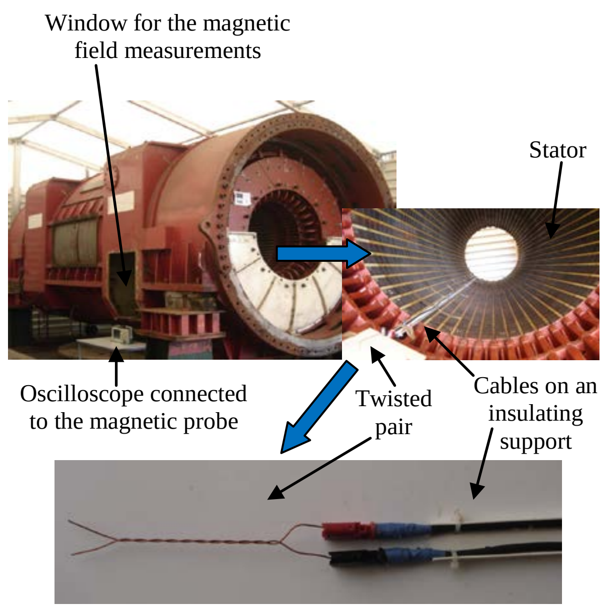

Fig. 3. An instrumented 125 MW stator available in LSEE.

To validate the proposed method of PD detection by magnetic field measurement, it is imperative to perform at the same time another conventional method. However, previous tests allowed the identification of partial discharge attendance by voltage measurements [17-18]. Therefore, voltage measurement corresponding to the propagation of the PD pulse along the cable (Fig. 4) is opted for this test. This signal goes through a high-pass filter (fc=100 kHz), eliminating 50 Hz component. The oscilloscope synchronized on the PD voltage records the voltage and the signal of the magnetic sensor.

The experimental arrangement is illustrated on Fig. 4. The AC voltage supply is placed at the input side of the cables. It includes a low-pass filter with a capacitor (5nF) considered as a low impedance voltage source for the high frequency phenomena in the line.

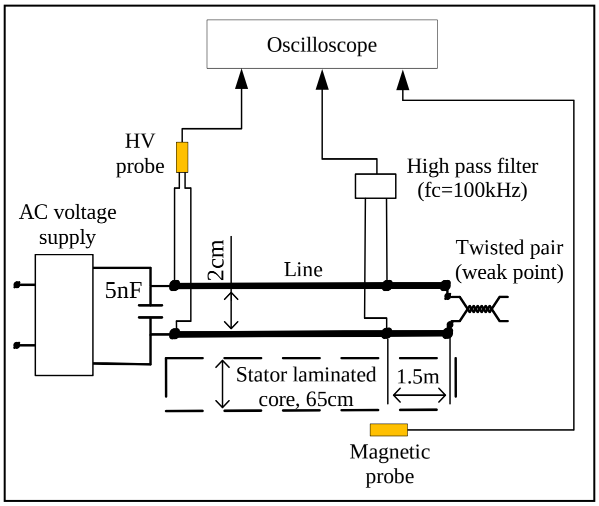

Fig. 4. Experimental system.

In order to initiate partial discharge in the circuit, the applied voltage must exceed the partial discharge inception voltage (PDIV) of the twisted pair (the weak point). This value has been measured with the twisted pair alone. Figure 5 illustrates the measurement of PDIV (> 700 V - 50 Hz) and its corresponding impulse current. There is a succession of short current pulses (mA, ns), which is a classical form of PD attendance [3, 13-14].

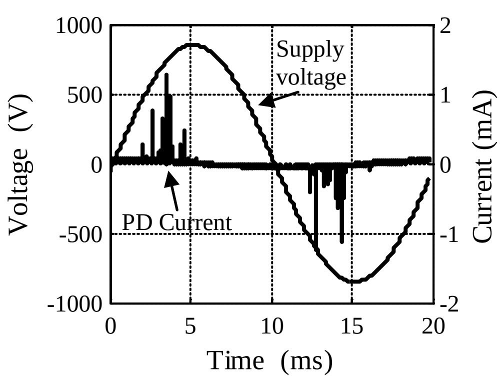

Fig. 5. Partial discharge current (AC-50 Hz).

For the field measurement in the second step of tests, the probe is placed in the cooling gap, between the external face of the stator laminated core and the frame. So the sensor is installed at 65 cm from the cables, which corresponds to the thickness of the stator laminated core.

The detection of such a low level flux density is difficult but not impossible when the sensor is suited to the problem. The sensor is a 4 turns flat coil printed on a PCB, its cross section of 22,5 cm^2. According to Faraday's law, the induced voltage measured by the coil is determined by the time derivative of the flux density. For this application, the induced voltages are in the range of millivolts; therefore amplification is necessary. The global amplification (G=100) is obtained using two low noise amplifiers AD8099. The bandwidth is 550 MHz, so the differences in pulse shape in the nanosecond range are measurable. The PD probe is connected to the oscilloscope via 50 Ω adapted coaxial cables.

B. Experimental results and interpretation

According to the testing protocol previously described, the first measurement is performed outside the stator. The propagation of partial discharge is verified. Figure 6 shows voltage measurement on the cable, in response to a PD pulse.

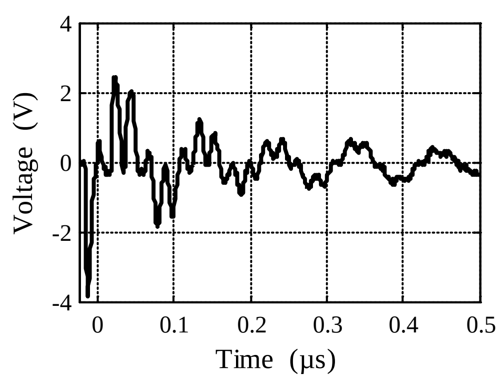

Fig. 6. Voltage pulse measurement on the cable.

The partial discharge is also detected by the magnetic sensor. The induced voltage measured by the probe is used to calculate the magnetic flux density from Faraday's law, by taking into account the amplifier gain (G=100). Figure 7 illustrates the flux density corresponding to the partial discharge.

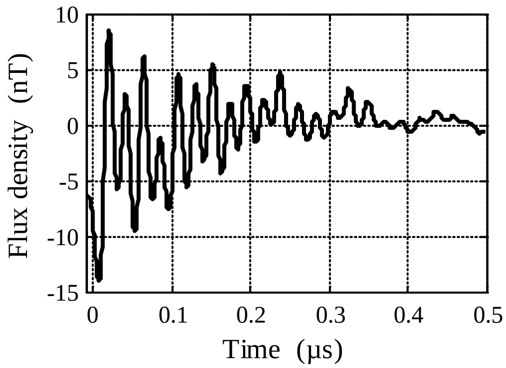

Fig. 7. Flux density due to the partial discharge measured outside the electrical machine.

Note on Fig. 6, that partial discharges (PD) excite resonances found also on the magnetic measurement (Fig. 7). Thereafter, the same measurements are performed by introducing experimental setup (line and twisted pair) inside the stator. The measurement of PD voltage pulse on the line is given on Fig. 8 and the corresponding magnetic field, measured in the cooling gap, is presented in Fig. 9.

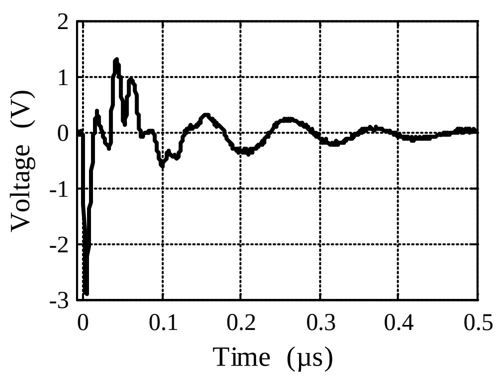

Fig. 8. Voltage measurement inside the stator.

From magnetic field measurements, it can be seen that the magnitude of the flux densities are the same range (Figs. 7 and 9). These results show that the stator laminated core is almost transparent for transient caused by partial discharge in the line equivalent to stator bars. Let us note that the damping is not the same. That can be interpreted by the induced currents in the stator bars, which are made of massive copper. The two measurements are made in the same experimental conditions, PD activity is similar but considering the stochastic nature of PD, it is impossible to have exactly the same PD pulse.

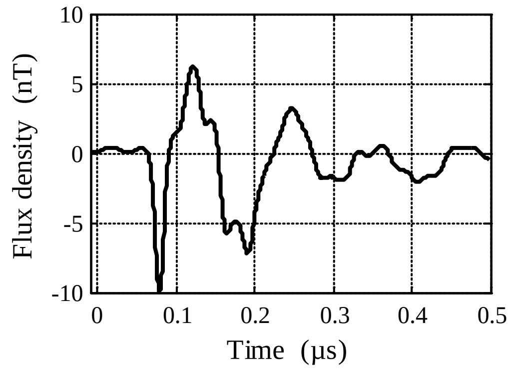

Fig. 9. Flux density due to the partial discharge measured in the cooling gap between the stator core and the frame.

From the measured flux density, the PD current can be estimated, considering a transparent core. This allows calculating the current as done before, considering air between the measurement point and the cable. It is shown in the figure below.

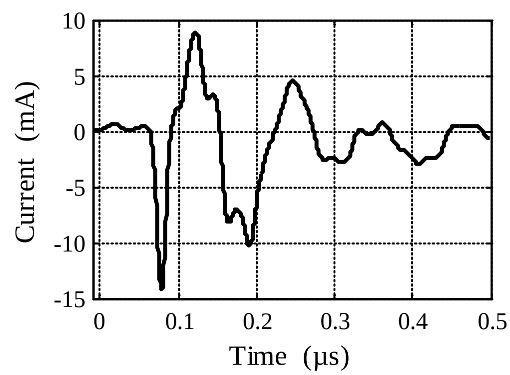

Fig. 10. Partial discharge current in the cable.

V. RESULTS INTERPRETATION WITH A SIMULATION TOOL

The interpretation of the measurement can be detailed using a model of the line simulated by PSpice. The equivalent circuit of the line is connected, at one side, to a current generator which simulate the partial discharge and, at the other side, to the real circuit of capacitor of the power supply filter.

The equivalent circuit of the cable is composed of five sections; their length is much shorter than the wave length at the considered frequency. The parameters of each section are determined using classical analytic formulae of capacitance and inductance and verified by measurement on a cable sample. The resistances corresponding to losses are also obtained using an impedance analyzer.

The voltage source is modeled by the equivalent circuits of the output filter capacitor (5 nF), which parameters are measured with impedance analyzer. The PD is assumed to be a square current pulse with duration of 1 ns and amplitude of 10 mA, so a charge of 10 pC.

Firstly, the Pspice model is used for frequency analysis (Fig. 11). This allows finding the first resonance frequency at 10 MHz which correspond to the oscillations frequencies observed on the measurement results (Figs. 6-10).

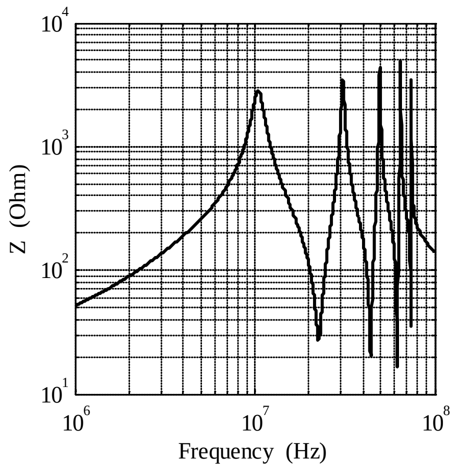

Fig. 11. Frequency analysis of the equivalent impedance of the cable.

Secondly, PSpice model is used to display the current and voltage in different point of the equivalent circuit.

Figure 12 illustrates the PD current calculated at the same point on the cable as in measurements (Fig. 10). It shows a correlation between the results in terms of resonance frequencies and the duration of the following transient state. Since it is difficult to reproduce the same partial discharge pulse during tests, the current amplitudes on Figs. 10 and 12 are different.

These simulation results confirm that the measured field is characteristic of the transient response of the equivalent line excited by a partial discharge current pulse.

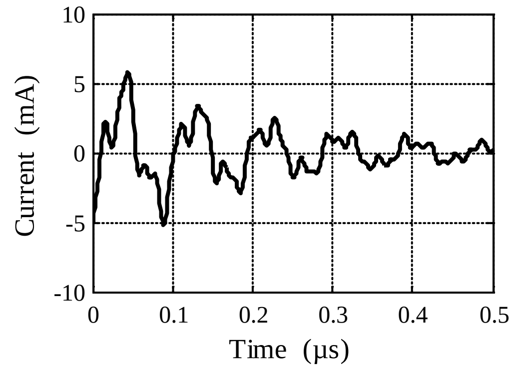

Fig. 12. PD current calculated from the equivalent model.

VI. CONCLUSION

This paper presents a prospective method for partial discharge detection in large ac machine. It shows that it is possible to measure and localize partial discharges in the stator bars by introducing a specific magnetic sensor in the cooling gap between the magnetic core and the machine frame.

The design of the sensor must be performed knowing the main resonance frequency of the stator bars, which depends on the geometry of the copper bars and the permittivity of the insulation between bars.

To be effective the low noise amplifier must be located near the sensor, therefore in the cooling gap. This circuit can monitor continuously PD, with a minimum amount of electronic components, which implicates very low space consumption.

With the proposed method, as it is possible to evaluate the partial discharge current, it will be possible to find a good quantification of the PD charge. This can help to evaluate the critical limits of degradation bars insulation.

Finally, it would be interesting to place more sensors around the stator in the cooling gap. This will allow greater efficiency of this PD detection method. These sensors must be small, cheap and autonomous. Due to the advances in analog electronics and wireless transmission systems, it is possible to develop energy self-sufficient sensors, powered by the leakage flux at the network frequency, on condition to transmit information for short times and at defined period.

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