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Evaluation of inter-turn stresses in electrical machines considering common mode elements

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Abstract- In the context of the more electric aircraft (MEA), and with the development of hybrid or all electric propulsion systems, future aircrafts will require electrical machines with voltage levels and switching frequencies higher than the reference values of 540 V and 10 kHz, respectively. During voltage transients, windings of electrical machines undergo overvoltages due to waveform reflection phenomena and non-uniform voltage distribution. These phenomena are amplified using modern PWM (Pulse Width Modulation) inverters built with SiC (Silicon Carbide) and GaN (Gallium Nitride) transistors. As a consequence, there is a risk that the inter-turn voltage may be higher than the PDIV (Partial Discharge Inception Voltage). In this context, it becomes crucial to precisely determine these inter-turn voltages. This paper focuses on a High Frequency (HF) model, which aims to predict the inter-turn and turn-to-ground voltages in electrical machines.

I. INTRODUCTION

Aeronautics has recently started major modifications in the on-board electrical network to provide more power and electrify more functions that are essential to the aircraft. To increase the power available, an increase of current cannot be considered because an increase of the weight of the on-board cables is not acceptable. Therefore, an increase of the voltage is examined, and futures aircraft could have an on-board network up to 3kV [1].

In this context, Partial Discharges (PD) could occur in electrical machines insulation system. Indeed, if the voltage is higher than the Partial Discharge Inception Voltage (PDIV), PD will “only partially bridge the insulation between electrical conductors” [2] and deteriorate the Electrical Insulation System (EIS). They will reduce the insulation performance (such as lifetime) and can lead to its premature failure by breakdown or arc fault. Moreover, some parameters of the voltage signal, such as voltage waveform and rise time, can have an influence on the inception of PD [3]. The most common criterion for the prediction of PD is the Paschen’s curve. It is based on experiments, and it depends on the pressure and the distance between electrodes to determine the PDIV.

During voltage transients, overvoltages occur at the machine terminals due to waveform reflection phenomena [4]. The overvoltage amplitude can reach up to twice the input voltage [5]. In most cases, stator windings are the first to suffer deteriorations, especially the inter-turn insulation, due to non-uniform voltage distribution along the winding turns. Therefore, it is necessary to predict transient voltage distribution within stator windings. Based on the transmission line theory, many studies were made to predict the turn voltages, using RLC circuit models [6]-[8]. However, [6] and

[7] consider only one coil or one phase of the electrical machine and so, neglect the common mode effects. While [8] consider the common mode but the feeder cable is not included in the turn analysis.

This paper presents a method based on a two scales model, to predict the inter-turn voltages, taking into account the common mode effects and the feeder cable. The objective of the first scale is to study the electrical machine at the power system level, i.e. when fed by an inverter using PWM (Pulse Width Modulation) control signals, focusing on long duration signals (several periods of the machine currents). In this case, the elementary coil is represented by an HF equivalent circuit whose parameters are determined experimentally. This first scale model allows determining precisely the inter-coil voltages taking into account the common mode elements generated by the PWM controller. The second scale model consists in studying the voltage distribution along the turns of one coil, using voltages determined previously. The parameters of the second scale model are calculated using Finite Element Methods (FEM).

II. DESCRIPTION OF THE SYSTEM

In this paper, a star-connected-3-phase-motor is considered. The neutral point is not connected. Each phase is composed of 4 elementary formed-wound coils. Each coil is placed in an electrical machine slot as shown in Fig. 1. Each coil is composed of 32 turns of flat wires, divided in 4 rows and 8 lines in the 2D plane. The size of the copper conductors is 5.06mm×1.62mm and they are coated with an enamel layer with a thickness of 35.77µm. They are placed in a laminated sheet stator and the winding is distributed.

III. FIRST SCALE MODEL

In a first approach, the electrical machine is supplied with a PWM-controlled inverter signal. The objective of this scale is to study the system electrical machine with the inverter and the feeder cable for several periods of time and to determine the “critical” edges. The coil model and the analysis of edges follow the method proposed in [10]. For an ideal PWM signal, the voltage between the phases and the neutral point (V_{AN} , V_{BN} , V_{CN}) can have five different values: 0, $\pm V_{dc}/3$ and $\pm 2V_{dc}/3$, where V_{dc} is the DC (Direct Current) bus voltage, fixed at 540V. Regarding the overvoltages, a rising edge from the PWM signal is considered as “critical” when its amplitude is higher than $2V_{dc}/3$ i.e. $> 360V$ in this case, as shown in Fig. 2, a. It is assumed that during the critical edges, the inter-turn voltages would be the highest and they represent the worst case.

Determining the critical edge allows to reduce the analysis of the turn-to-turn voltage to only one edge. Representing the 3-phase-electrical machine allows to take into account the common mode.

The PWM voltage signal is obtained by a comparison of a triangular and a sinusoidal signal, whose frequencies are 20kHz and 1kHz respectively (Fig. 3).

The rise time of the rising edges is 54ns and the slew rate (dV/dt) is 10kV/μs. The machine terminals are connected to the inverter via a 1m input cable; the circuit model used to represent this cable is based on the model developed in [9] (Fig. 4). In addition, an impedance Z_{OG} of 1Ω is placed between the ground and the input of the voltage source (Fig. 5).

The circuit model used during the first approach is shown in Fig. 5. Parameters are determined for an elementary coil, using the method presented in [12]. Using this method, it is assumed that each coil is independent from the others. The impedance measurements realized by an impedance analyzer from 40Hz to 110MHz are presented in Fig. 6; from these measurements, three study points are chosen: low frequency point, parallel resonance and series resonance. At low frequency, the inductance L_c is supposed constant, and it is calculated supposing the series resistance is negligible. The parallel resonance corresponds to the maximum of the impedance modulus, where the series resonance corresponds to the minimum of the impedance modulus following the parallel resonance.

The first branch with R_p ($R_p=2.14e-3\Omega$) represents the iron losses, deduced from the admittance calculation, the second one the parallel resonance ($R_c=89e-3\Omega$ and $L_c=2.47e-3H$) and the

third one the series resonance ($R_s=7.96\Omega$, $L_s=2.47e-6H$, $C_s=6.98e-11F$).

The equivalent circuit is realized with SPICE and the frequency simulation has a good correlation with the experimental results as shown in Fig. 6. The differences between experimental and simulated results are due to the non-linear behavior of the iron, which is difficult to take into account.

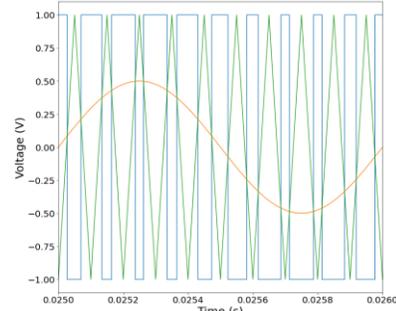


Fig. 3: Comparison between triangular and sinusoidal signal for PWM

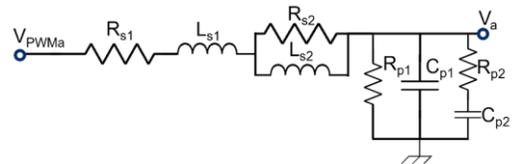


Fig. 4: Input cable circuit [9]

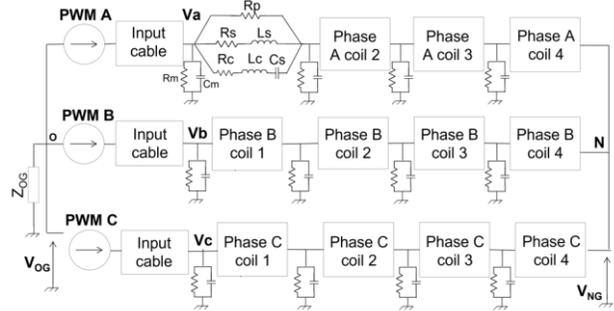


Fig. 5: Equivalent circuit for the electrical machine (first scale model) [10]

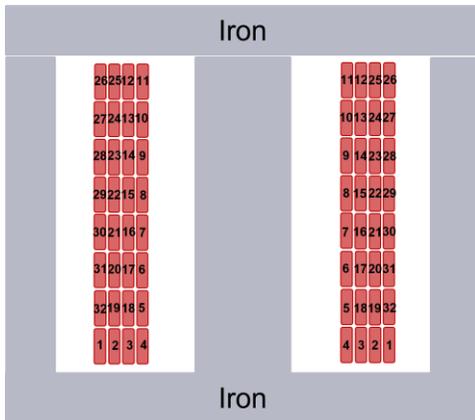


Fig. 1: Elementary coil in stator tooth

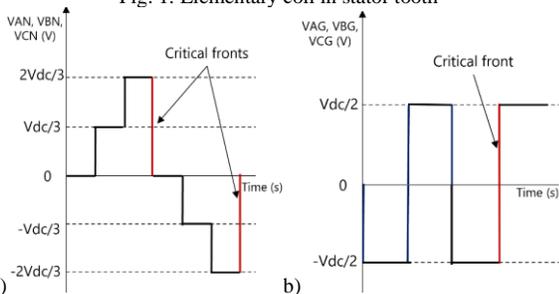


Fig. 2: a) Determination of the critical edge of the voltage between the phase and the neutral (V_{XN}) for a perfect PWM, b) Determination of the critical edge of the voltage between the phase and the ground (V_{XG}) for a perfect PWM

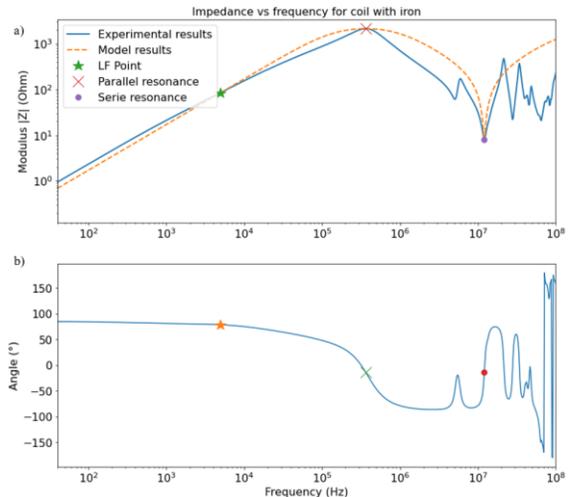


Fig. 6: Impedance measurements vs frequency done with an impedance analyzer for the determination of the parameters of the first scale model: a) the modulus, b) the phase

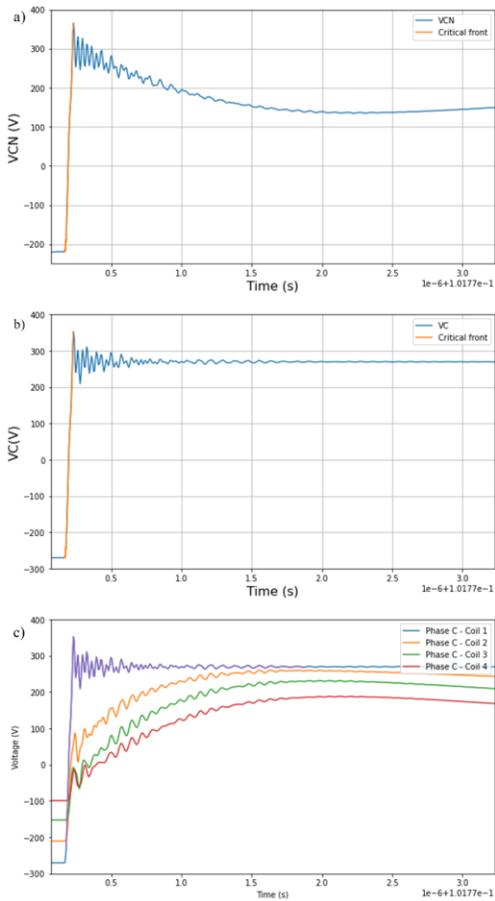


Fig. 7: a) Voltage between the critical phase (C) and the neutral during the critical edge, b) Voltage between the critical phase (C) and the ground during the critical edge, c) Distribution of the voltage between coils and ground during the critical edge

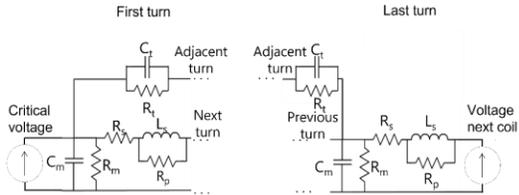


Fig. 8 :Turn equivalent circuit from [11]

To obtain the coil voltages of each phase, a 120ms transient simulation is realized and the analysis is done after 100ms. An analysis of the edges of each phase-to-neutral voltage V_{XN} (with $X=A,B$ and C) is realized to determine the critical one. In our case, the critical edge is obtained for phase C. The initial value of V_{CN} is $-218.83V$ and its final value is $365.74V$, as presented in Fig. 7, a). The difference between the initial and the final value is $584.57V$, so higher than the threshold of $360V$ determined before.

After determining the critical edge from the phase-to-neutral voltage V_{XN} , the critical edges from the voltage between the phase and the ground (V_{XG}) are studied, as presented in Fig. 7,b .

The rise time of the edge V_{CG} is $61.8ns$ and with a slew rate of $10.06kV/\mu s$. The initial value is $-269.72V$ and the final is $352.66V$. The results are shown in Fig. 7 , b. The overvoltage

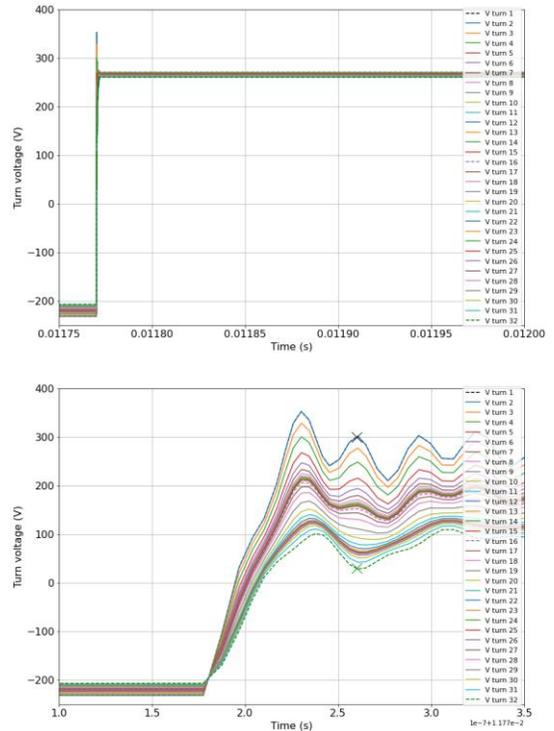


Fig. 9: a) Turn voltages with the steady state b) Turn voltages during the transient part

for the first coil is 30.6% of the DC bus voltage. The first coil is the one with the maximum voltage, so its characteristics are used for the second scale model (at the turn level). Finally, the voltage of each coil of phase C during the critical edge are represented in Fig. 7.c.

IV. TURN ANALYSIS

After determining the coil voltage, the model is discretized by turns; the equivalent circuit is shown in Fig. 8. Each component represents an electromagnetic phenomenon involved occurring at the turn level: Joule losses (R_s), iron losses (R_p), dielectric losses within the conductor insulation (R_i) and at the core insulation (R_m), magnetomotive force (L_s), the mutual magnetomotive force generated between two conductors (M), inter-turn capacitances (C_t) and turn-to-ground capacitances (C_m).

The calculation of these parameters is made in two steps: in a first step, a frequency analysis is made to determine the resonance frequency of the system.

In a second step, only resistances and inductances are calculated at the resonance frequency due to their frequency dependency. In this case, the calculated resonance frequency is $1.46 \times 10^5 Hz$, close from the experimental resonance used for the determination of the parameters in Fig. 6, which was of $3.15 \times 10^5 Hz$.

The parameters are determined by FEM using GMSH [13] and GetDP [14] softwares, following the method proposed in [11]. A magneto-dynamic analysis is used for the calculation of self and mutual inductances, self-resistance and iron losses resistances. The inter-turn and turn-to-ground capacitances, as

well as dielectric losses resistances are calculated using an electrostatic solver.

The equivalent circuit is realized for the coil presented in II using SPICE software. The critical voltage, identified previously for coil 1 is applied at the input of the turn 1, where the voltage of coil 2 is applied at the end of the turn 32 as shown in Fig. 8.

The results from the simulations are presented in Fig. 9. The first figure shows the complete edge, while the second figure presents the distribution of the transient voltage. It can be seen that the first turn undergoes the maximum voltage while the last turn is the one with the lowest voltage level. Given that the first and last turn are adjacent from a geometrical point of view, as shown in Fig. 1, one can consider that the corresponding inter-turn voltage constitutes the weakest point for this winding configuration. This phenomenon is due to the propagation of the waveforms and the reduction of the rise time of the waveforms along the winding. The rise time of the last turns is much lower than that of the first turns. In this case, the inter-turn voltage is 273.63V (Fig. 9, b), which is lower than the minimum of Paschen's curve in air at atmospheric pressure. In addition, it can be seen that the first turn undergoes an overvoltage of around 31% of the DC bus voltage, while in the case of the other turns, the overvoltage decreases until there is no more overvoltage from turn 5 onwards.

ACKNOWLEDGMENT

In this paper, a method based on a two scales model was proposed. The first scale model deals with a coil analysis considering the environment of the electrical machine fed by a PWM control inverter and the input cable. The parameters of the first scale model are determined by an experimental frequency analysis. The edges of the input voltage were studied, and critical edges were identified as the ones for which the highest voltage difference between initial and final value is observed. This criterion will be improved in a future work by including a deeper analysis of different edges and considering other parameters such as the rise time and the difference between positive and negative edges. A comparison with experimental results from a slot composed of an elementary coil will also be done.

The study at the coil scale allows having a representative equivalent circuit of the system (electrical machine + inverter + input cable).

In a second step, the analysis was reduced to study only one coil at the scale of the turn. Parameters were determined by FEM with an electrostatic and a magneto-dynamic analysis.

Based on a 540Vdc voltage network, the maximum inter-turn voltage observed (considering overvoltage) was of 273.63V, below the minimum of Paschen's curve in air, which is of 327V, but considering the increase of the on-board voltages and, in particular, the use of 800V+ V DC bus voltages, the overvoltage could be problematic from a PD point of view. Future works will focus on PD inception in electrical machine's windings based on the two scales model presented in this paper. An in-depth study of the inception of partial discharge with this two-

scale method will also be done. Finally, the comparison between the model and experimental results will be realized.

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