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A general model to compute the electric flux lines in the slots of electric machines for the evaluation of partial discharge risk

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Nowadays, on board electric machines of higher specific power powered by faster inverters represent a real challenge in designing the electrical insulation system (EIS). The electric stress on the stator winding is increased and thus partial discharges (PD) are more likely to appear. The Paschen's criterion is widely used to evaluate the PD risk. This paper presents a general method to compute the electric flux lines in the slots of electrical machines. A 2D model of an electric machine slot is solved in term of electric scalar potential. Then, from the nodal scalar potential solution, electric flux lines are located inside the slots. Consequently, the Paschen's criterion is applied by taking into account the real flux lines length. Some applications are presented to highlight the usefulness of the method to solve industrial problems.

Index Terms—partial discharges, dielectric constant, electric motor, numerical model

I. INTRODUCTION

THE AERONAUTIC industry is looking towards the “more electric aircraft”. The European Union (EU) is continuing the Clean Sky program which announces electric motors with high specific power of about 5 kW/kg in 2025 and 10 kW/kg in 2035 [1]. To obtain such high specific power, increasing the DC bus voltage beyond the classic industrial voltage, which served as reference in the design of EIS, may be a solution. However high dV/dt due to the switching frequency of the inverters results in higher electric stresses on the stator winding [2]. In research, the Paschen's criterion [3] is widely used in the prediction of partial discharge (PD). Finite element method has already been used in order to evaluate partial discharges risk between 2 round wires [4]. This paper presents a model to predict PD in a whole stator slot filled with conductors the aim of the model is to accurately compute the voltage drop along a field line and its length. If the voltage drop along a field line is greater than the reference voltage given by its length and the Paschen's law, one can conclude that there may be PD on this field line. Firstly, a state of the art on the use of 2D electric field model to evaluate partial discharge risk between two conductors is presented. Subsequently a general method to compute electric flux lines inside a whole slot is described. An application finally shows the use of this method to evaluate partial discharge risk in slots.

II. AN EVALUATION OF PARTIAL DISCHARGE RISK

PD are difficult to predict. In [3] a finite element, an analysis is used in order to calculate the electric potential between 2 round enameled copper wires in the air. The flux lines are assumed to be straight lines. The lengths of these straight lines are calculated from geometric relations. For each flux lines, the Paschen's criterion is calculated from the voltage drops along the lines and their approximated lengths and compared to the Paschen's law to conclude on PD risk.

Another approach can be found in [4]. The authors also focused on the electric field between 2 round enameled copper wires. Two electric field models are used. The first uses the electric scalar potential V to obtain the electric potential anywhere between the two conductors. The second model uses the electric vector potential \mathbf{u} . In 2D model the electric flux lines are the equi- u_z lines. The knowledge of the electric flux

lines allows precisely calculating their lengths and the voltage drops along these lines thus PD risk are more accurately evaluated than in [3].

III. MODELING THE ELECTRIC FIELD

In this work, as in [3] and [4], the voltage drops of the conductors along the direction parallel to the rotor axis are put aside the time dependency of the voltages is not taken into account. Due to both these assumptions, the electric field in a slot is modeled as a 2D charge free electrostatic problem. The stator slot is rectangular and unvarnished i.e filled with air at pressure $p=1bar$ of dielectric permittivity ϵ_0 . The winding is composed of round conductors. The conductors are covered with polyimide (PI) and the slot insulator is a PET film. The dielectric permittivity of PI and PET is taken to $\epsilon_r=3.5$. The potential of each conductor is imposed. They may be calculated from the knowledge of the winding, the electric parameters of the motor, the currents and the voltages during each phase. The electric potential distribution inside the slot is computed by solving Laplace's equation (1):

$$\nabla^2 V = 0 \quad (1)$$

This equation is solved by using a 2D nodal finite element method. To calculate the electric flux lines, one may use as in [4] an electric vector potential formulation however this formulation is not so easy to use when considering the electric field problem in the entire slot. Indeed, within the study domain, there are no electric charges and the divergence of the electric flux density is equal to zero. However, as the charge of each conductor is not zero, the total electric flux through the external surface of each conductor is not null either. Hence it is a multivalued potential problem in a nontrivial domain and it is not as easy as in the case of only two conductors [5].

The main goal is to build the real electric flux lines and to compute the voltage drops along these lines and their lengths. From the nodal values of the electric potential the equipotential lines are firstly determined and the lines orthogonal to these lines are computed from the nodal scalar potentials by solving the equation (2):

$$\mathbf{E} = -\mathbf{grad}V \quad (2)$$

IV. APPLICATION

A motor of specific power of 6kW/kg has been sized. A stator slot is filled with resin. However, the impregnation process is not perfect and some air bubbles are trapped in the resin. These air bubbles are weak points in which breakdown will occur first. In the model, the slot is considered as filled with air. By preventing PD occurring in this air-filled model, it is supposed that there will be no PD in air bubbles trapped in the real resin filled slot. The sections of the conductors and voltage levels have been calculated from this sizing. The hypothesis of an overshoot of 50% on the first conductor is made in order to take into account the effect of the mismatch of both cable and motor impedances. The winding parameters are summarized in Table I. The conductors are positioned in the slot in order to minimize the electric stress between conductors and between conductors and the stator iron which is assumed to be at ground potential. The copper sections of the conductors are unmeshed (the white areas in Fig 1.a). The electric scalar potential V is applied to the copper contour according to Table I.

TABLE I
WINDING PARAMETERS

Item	Value
Number of conductors	6
Number of round enamel copper wires/conductor	3
Total number of wires in the slot	18
Enamel thickness	46 μ m
PET sheet thickness	100 μ m
Conductor diameter	4.2mm
V_{cond1}	3.953kV
V_{cond2}	2.519kV
V_{cond3}	2.404kV
V_{cond4}	2.289kV
V_{cond5}	2.176kV
V_{cond6}	2.063kV

Therefore, the study domain is constituted of the air, the black zone in Fig. 1a due to very fine mesh, replacing dielectrics in the slots and the insulation covering the conductors. The boundary conditions are shown in Fig. 1a: on the red boundary, normal field conditions are applied, on the green boundary a tangential field condition is applied. The mesh is refined around the conductors under study (Fig 1.a). The computed electric flux lines are sampled into segments. The length of one flux line is obtained by totaling all the elemental segment lengths. Such flux lines are shown in Fig 1.b. The color scale represents the voltage distribution. In Fig 1.c, the voltage drops along the flux lines in the zoomed region are compared to the Paschen's curve: there is probably a PD risk in this zoomed region.

This comparison can be done with all the flux lines in the slot. It will be shown that in this case there are some regions where a PD risk exists. The PD risk may be studied according to the permittivity inside the slots, the location of the conductor or the filling factor. In the final version, the case

with a floating stator iron potential will be studied. This case will necessitate taking into account the whole stator.

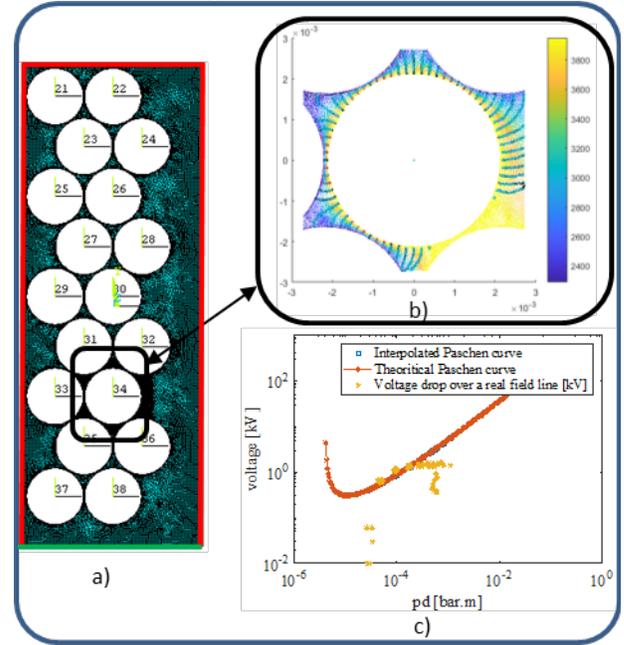


Fig 1. A Mesh of the finite element model (a). Real electric flux lines between 5 conductors (b). Computed voltage drops along the flux lines versus Paschen's curve (c)

V. CONCLUSION

This paper introduces an original model to predict a PD risk. This model is used in a tool under development to help the machine designer to take account of the PD risk (or : to take the PD risk not account. This tool is aiming to be fully automatic.

VI. ACKNOWLEDGMENT

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