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# **A PROPOSITION FOR IMPROVING THE DESIGN OF MOTOR WINDINGS FOR LOW-PRESSURE ENVIRONMENT**

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## **ABSTRACT**

In low pressure environment, partial discharges (PDs) appear for lower voltages, shortening strongly the machines life times fed by PWM inverters. A new approach is proposed for designing AC motor windings free of PD at low pressure. The method consists of adding a thin resistive layer on the outer surface of the enameled wire used for winding the machine. Thereby, PDs occur only in critical zones, near the wire connections, rather than randomly in coils. Consequently, a coil design with a small additional quantity of varnish in critical zones can increase strongly the partial discharge inception voltage (PDIV). The paper propose a theoretical analysis of the improvement based on Paschen's law for its application in non homogenous electrical fields.

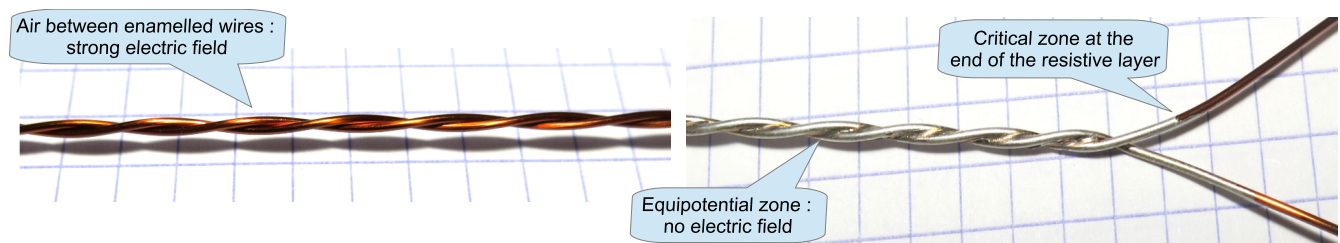
## **INTRODUCTION**

In recent airliners, the electrical energy takes a larger and larger place because it brings many advantages comparing to hydraulic and pneumatic ones. For increasing the electric power, the aircraft industry has chosen higher voltages, switching from 115 VAC to 540V DC. High power density electric actuators are connected to the 540V DC grid by inverters that provide an efficient machine control and a full reversibility of the power. However, the electronic switches of the inverters impose steep-fronted voltage pulses that cause repetitive short voltage spikes in the machine windings and cause PDs and an earlier aging of the machine Electrical Insulation System (EIS), when their magnitudes exceed the PDIV [1,2]. For Permanent Magnet Synchronous Motors (PMSM), the winding can be made with concentrated windings (one coil per stator tooth), with a deterministic design of coils. The exact position of each turn is known and the coil design can he made for getting a good distribution of voltage spikes endured by the turn-to-turn insulation [3]. Cheaper induction machines are also used but they need distributed windings. The coils of such motors have a random topology. The turn-to-turn voltage may be large because the probability to have the input turn near the output one is not negligible. The thin insulating layer of the enameled wire and the residual air between them must resist to a high voltage stress and PDs may appear inside coils. The

paper proposes technological solution that consists of adding a thin resistive layer on the outer surface of the enameled wire. This layer reduces the electric field in the residual air voids between the turns and concentrates the electric field in the polymer. However, a critical zone appears near the wire connections, where the enameled wire must be stripped. The paper details theoretical investigations able to compute the PDIV in such critical zones.

## PRINCIPLE OF THE PROPOSED IMPROVEMENT

In a motor coil, the outer surfaces of the wires are in contact together. Consequently, at a microscopic scale, the additional resistive layers on each turn create equipotential surfaces that reduce strongly electric field in the air between turns: the electric field is concentrated in the thin polymer layer that covers the copper wire. The motor industry uses specific polymers able to withstand much higher electrical fields than air; the field concentration in this material does not cause any problem. With the thin resistive additional layer, the critical zones, corresponding to high field magnitudes in air, are moved towards the ends of the enameled wire, where it must be stripped for performing connections. In these critical zones, the insulation must be reinforced for avoiding PDs. Experimental investigations that confirm this phenomena were carried out on twisted pairs made following IEC 60172 standard [4,5]. In figure 1, the left picture shows such a standard twisted pair and the right one shows a similar twisted pair with an additional thin external layer made of a silver conducting paint.

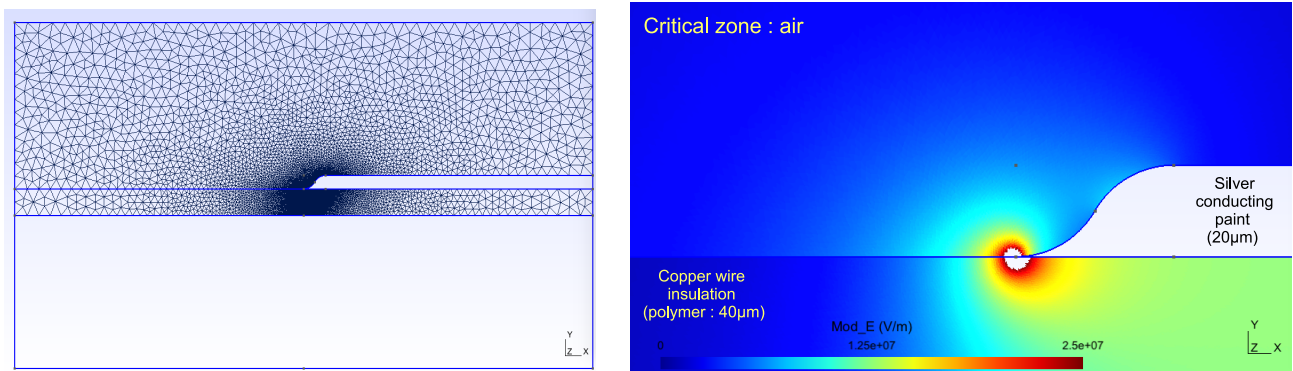


**Figure 1: Picture of a standard twisted pair and another one covered with a silver conducting paint layer.**

## ELECTRIC FIELD IN THE CRITICAL ZONES

A finite-element (FE) electrostatic simulation is performed for computing the electric field in the critical zones where PDs may appear. The electric field is computed in the polymer layer and in the ambient air. Figure 2a shows the 2D FE model of the electrostatic problem built at the micrometer scale. A dense mesh is applied in the critical zone of air near the end of the conducting paint. Figure 2b presents the color map of the electric field in the critical zone of air for 500V applied between the copper wire and the silver conducting paint. This voltage corresponds to half the peak voltage of experiments, because

twisted pairs are supposed to be made of two identical wires. The highest field values, where PDs may appear are concentrated near the end of the silver conducting paint.



**Figure 2: a) Geometry and mesh of the critical zone.**

**b) Electric field in the critical zone.**

With the FE simulation results, a detailed analysis of this zone can be made using Paschen's theory for predicting the PDIV of the twisted pair covered by silver conductive paint. Let us remind that, more than a century ago, Paschen studied the ignition of the ionization of a pressurized gas under an electric field [6]. At the same period, Townsend worked on gas ionization processes, where free electrons are accelerated by electric fields [7]. Similar studies were performed for typical non-uniform fields due to specific electrode shapes used for high-voltage applications [8]. These approaches are based on the acceleration of free electrons, in the free path between gas molecules, at a given pressure. At high pressures, the free path between gas molecules is short; the accelerated electrons give up their energy in a series of non-ionizing collisions. At very low pressures, the free path between molecules is long. The accelerated electrons reach the anode before colliding with a gas molecule. In both cases, there is no gas ionization. PD appears when the accelerated free electrons acquire enough energy for ionizing gas molecules when they collide. The ionization initiates an electronic avalanche and a complex chain reaction leads to a gas breakdown for naked electrodes. The Paschen's empiric law, which defines the breakdown voltage in a pressurized gas, is still a reference. This law result of many experiences made with two plane metallic electrodes. Therefore, the electric fields of Paschen's experiences were uniform as the the forces applied to free electrons. In practical cases of electrical machines, the electric field is never uniform. Figure 3 shows the field lines in the critical zone of air for our problem, they are computed by the finite element analysis. The lines are curved; their interesting parts start from the polymer surface and end on the silver conducting paint. Unlike Paschen's experiments, the electron inertia may have an influence. The consequences of this major difference must be carefully studied before applying Paschen's law. The basic question is: "Do free electrons follow the field line as they do in the Paschen's experiences?". For answering this question it is supposed the voltage is equal to the PDIV, which corresponds to the ignition of the electronic avalanche. With such a

voltage, the electric field accelerates a free electron until it acquires a kinetic energy equal to molecule ionization one, then an ionizing collision occurs and absorbs this energy. Another free electron is created and accelerated by the field. With this simplifying hypothesis, it is possible to estimate trajectory of free electrons by solving the mechanical equation of a solid object placed in the field force ( $\vec{F} = q\vec{E}$ ) defined in the critical zone.

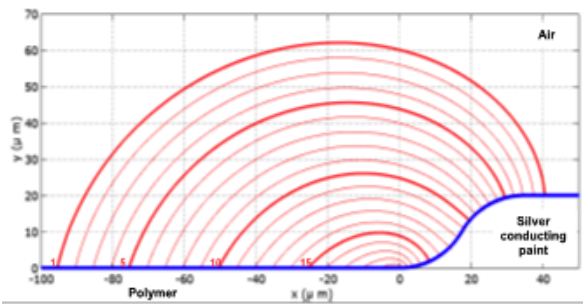


Figure 3 : Field lines in the air of the critical zone.

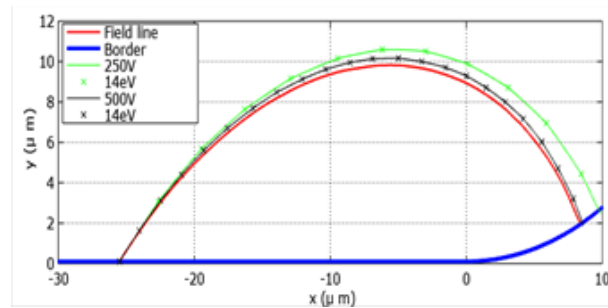
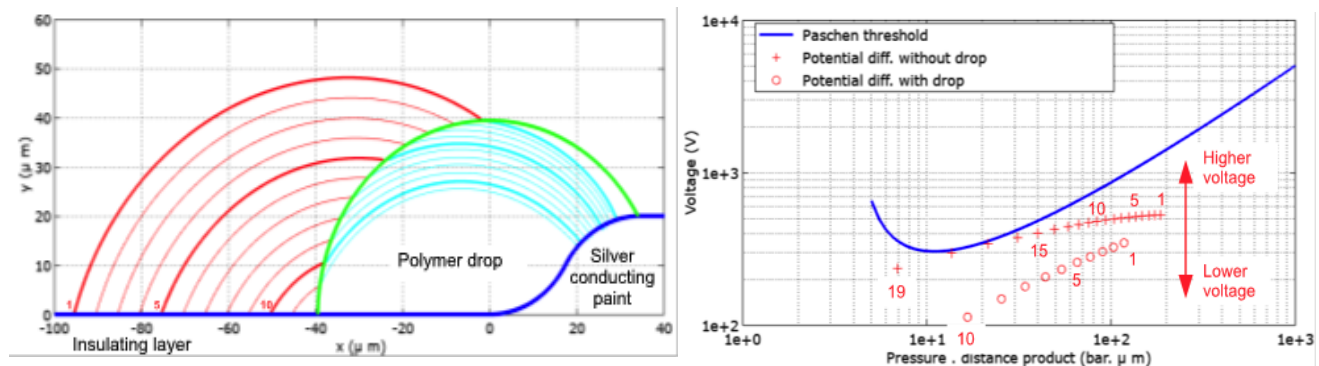


Figure 4 : Trajectories of free electrons and field line 15.

These very restrictive hypotheses suppose that the voltage imposed to the twisted pair, corresponds exactly to the PDIV, at a given pressure. The random aspects of the problem are also neglected. The mechanical problem is solved considering the electron mass  $m = 9.109 \cdot 10^{-31} \text{ kg}$ , its charge  $q = -1.602 \cdot 10^{-19} \text{ C}$  and ionization energy of gas molecule of 14 eV. The air is supposed to be made only of nitrogen and oxygen and the ionization energy of these molecules are supposed to be the same (13.6 eV for oxygen and 14.5 eV for nitrogen). Figure 4 shows simulation results of the mechanical problem that consider the mass of moving electrons. A free electron at zero speed is supposed to appear at the origin of the field line 15 in Figure 3, on the polymer layer. Two voltage levels correspond to the PDIV in air at atmospheric pressure and half of atmospheric pressure. The time step used for solving the mechanical equation is  $0.01 \text{ ps}$  and mechanical equations are solved for a square mesh is  $0.5 \mu\text{m}$ . The electrons trajectories are not exactly superimposed to the field lines; the differences are higher for lower voltages. The small crosses plotted on the electron trajectories correspond to ionizing collisions with a  $\text{N}_2$  or a  $\text{O}_2$  molecule considering an average energy of 14eV. In this figure, the field line length is  $40 \mu\text{m}$ ; the electron trajectories are  $41.5 \mu\text{m}$  for 250V and  $40 \mu\text{m}$  for 500V. This simplified approach shows that, for the considered geometry, the field line curvatures can be neglected at ambient pressure, but not for low pressures. A small ball of insulating varnish change greatly the field lines in the critical zone. Figure 5 shows the field lines obtained adding a small drop of varnish, which relative permittivity is equal to 4. The shortest field lines are now in the polymer drop, which have a much higher breakdown voltage. PDs may appear in air between field lines 1 and 11. Figure 7 presents Paschen's curve in air at ambient temperature (blue line) and the simulation results for atmospheric pressure. On this figure, the "+" signs and the numbers corresponds to the field lines computed without any varnish drop (figure 3). The Pashen curve is reached for lines numbers

17 and 18; PDs occur along these lines. The “o” signs are plotted when the varnish drop exists; the points are far from the Paschen’s curve, the applied voltage is much under the PDIV.



**Figure 6: Field lines with drop of polymer varnish ( $\epsilon_r=4$ ). Figure 7: PDIV computation for atmospheric pressure.**

## CONCLUSIONS

The thin resistive layer on the external surface of an enameled wire removes PDs in the residual air between the turns of motor coils. The addition of the small balls of varnish in critical zones at the end of the resistive layer increases the PDIV of the coil. At atmospheric pressure, the accelerated free electrons follow the field lines and Paschen’s law can be used considering the length of the field lines and the potential differences between their extremities as Paschen made it. At reduced pressures the trajectories of the free electrons differ from the field lines; Paschen’s law cannot directly be used. However the principle described by Paschen and Townsend can be applied considering the actual length of the free electron trajectories and the potential difference between their ends for predicting the PDIV, at low pressures, in non-uniform electric fields. Details will be presented in the full version of the paper.

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