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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 proposes a theoretical analysis of the improvement based on Paschen's law for its application in non homogenous electrical fields.

I. 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 115V AC 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 induce 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 be made for getting a good distribution of voltage spikes endured by the turn-to-turn insulation [3,4]. 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 [5]. 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.

II. ENVIRONMENT OF AIRCRAFT EMBEDDED MACHINES

Two very different environments physical environments exist for embedded motors; they can be placed in the cabin or outside. For the first case, the air-control of the cabin provides classical temperatures at a pressure that gives comfortable conditions to passengers. In old aircrafts, the pressure corresponds to mountain conditions at an altitude of 2000m and a little less for recent aircrafts (1850m). The cabin pressure is more or less 80% of the sea-level pressure. However electrical machines can be placed outside the cabin where the environmental conditions are very different. Aeronautical engineers work with a standard atmosphere [6] that gives temperatures and pressures representatives of any point of the world. Table 1 gives 3 typical values. The lower pressure and temperature influence the performance of the Electrical Insulation System (EIS) of the electric actuator windings.

TABLE 1. PRESSURE AND TEMPERATURES DEFINED IN THE STANDARD ATMOSPHERE [6]

Altitude [m]	Altitude (feet)	Temperature (°C)	Pressure [hPa]
0 – sea level	0	15	1013
5000	16404	-17.5	541
10000	32808	-50	265

The motor windings are generally made with enameled wire and impregnated with a varnish that provides a mechanical coherence and better insulation characteristics. However, it is practically impossible to guarantee the absence of small air-voids between turns inside the windings. Partial Discharges (PDs) may occur in these air-voids during the voltage spikes caused by the PWM inverter that feeds the machine. When they exist, PDs accelerate the EIS aging by slow erosions, at a microscopic scale, of the thin polymer layer of the enameled wire.

It is well known that PDs apparition conditions depend on temperature and pressures in the small air-voids [7]. Two cases must be analyzed because the air-void can be internal, without any contact with the ambient air, or external at ambient pressure. For the first case, the air-void volume is

constant. The machine is generally made with the standard 3 phases “vacuum pressure impregnation” (VPI) at standard atmospheric pressure (sea level). During the first step, the liquid varnish penetrates in the motor winding placed in a partial vacuum. The second phase consists in applying a pressure to the whole system when the varnish is still liquid helping its penetration. The third phase consist in polymerizing the varnish in a hoven at ambient pressure. At the beginning of the polymerization process, the varnish is still liquid; the air-void volume change for getting a global pressure balance. The final volume of residual closed air-voids is fixed when the varnish becomes solid. Consequently, the initial data of closed air-voids can be estimated to the pressure in the polymerization oven $p_1 = 1013$ hPa and its temperature $T_1 = 120$ °C (393°K). The pressure at another temperature can be estimated using the perfect gas law $pV = nRT$. The product pressure volume depends on the number of gas molecule (n), the constant of the perfect gas (R) and the absolute temperature in Kelvin (T). Considering two absolute temperature T_1 and T_2 , the ratio of the corresponding pressures in a given air-voids is:

$$p_2 = p_1 \frac{T_2}{T_1} \quad (1)$$

Table 2 gives the estimation of gas pressures in closed air-voids at 3 altitudes computed by (1).

TABLE 2. ESTIMATION OF THE TEMPERATURES AND PRESSURES IN CLOSED AIR-VOIDS

Altitude (m)	Altitude (feet)	Temperature (°C)	Temperature (°K)	Pressure in closed air-bubbles (hPa)
0 – sea level	0	15	288	739
5000	16404	-17.5	255.5	658
10000	32808	-50	223	574

For opened air-voids the pressure is the atmospheric one at the considered altitude. The comparison of tables 1 and 2 shows that the pressure is much lower for opened air-voids. This case is more stressful for the EIS.

Paschen’s formulae (2) results of old experimental works on the breakdown voltage in gas a given pressure p , placed between two flat electrodes at a distance d [8]. This formula predicts the avalanche threshold V_{Th} at from the pressure distance product. The Paschen’s formula uses the old unit for the pressure (Torr); the constants A and B use these units. $A = 15Torr^{-1}cm^{-1}$; $B = 365VTorr^{-1}cm^{-1}$. $\gamma = 0.01$ is the second Townsend coefficient [9].

$$V_{Th} = \frac{B(p \cdot d)}{C + \ln(p \cdot d)} \quad \text{with } C = \ln\left(\frac{A}{\ln(1 + 1/\gamma)}\right) \quad (2)$$

Another old works made by Peek improve the Paschen’s law taking the gas temperature into consideration [10]. Peek propose a correction of Paschen’s threshold voltage V_{Th0} computed at room pressure (760Torr) and temperature (293K).

$$V_{Th}(p, T) = \frac{293}{T} \frac{p}{760} V_{Th0} \quad (3)$$

Recent experimental works confirm the Paschen’s law for the right part of the curve, for distances and pressure over the Paschen’s minimum [11, 12]. Another recent work confirms the Peek correction for very cold Nitrogen [13].

Figure 1 shows the corresponding curves for temperature and pressure in opened air-voids at 3 altitudes. The horizontal axis is the distance d between the flat electrodes of Paschen’s experiences. These curves can be used for estimating the partial discharge inception voltage (PDIV) at high altitude from a measurement made at sea level. The small circles added on this figure illustrate the case of a twisted pair made with a standard enameled wire whose diameter is 0.7mm. The PDIV measured at room temperature and pressure is $1.25kV_{peak}$. When the variation the polymer permittivity is neglected and considering the same geometry, Paschen’s curve, with Peek’s correction, predict a PDIV estimated to $420V_{peak}$ at 10000m. Consequently, for avoiding PDs in standard machines placed outside the cabin of airliners, the voltage spikes must be much lower. With out any change in the motor design, the supply voltage should be more of less 1/3 of the standard one, which is very disadvantageous for the drive global performances. Let us remind that Paschen’s experiences were made with flat electrodes that create uniform fields. In the opened air-voids of motor windings, the electric fields are not uniform. A more detailed analysis of Paschen’s hypothesis shows that Paschen’s law can be used with a reasonable error [14].

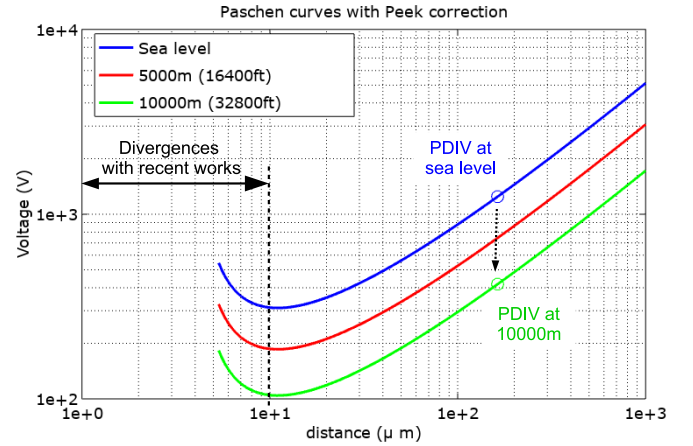


Fig. 1. Breakdown voltage in air versus the distance between flat parallel electrodes for 3 altitudes.

III. DRAWBACKS OF PDS IN A MOTOR WINDING

Traditional motor are wound with enameled wires made of a copper conductor insulated by thin polymer layers. The most widely used enameled wires are made with two insulating layers. The first one, in contact with copper, is a polyester-imide (PEI) providing a good adherence on the copper. The outer layer is made of polyamide-imide (PAI), which provides the mechanical and thermal properties [15]. The global thicknesses of the insulating layers depend on the diameter of the wire and its grade [16]. A typical polymer thickness is $40\mu m$ for a 0.7mm wire diameter. The enameled wire is manufactured with a complex industrial process, which consists in depositing several thin layers for getting the required global insulation thickness. Consequently, no significant air-void can exist inside the insulation layer of the enameled wire. PDs occur only in air-voids existing between turns or between wires and stator teeth. For both cases PDs

cause a slow erosion of the PAI layer of the enameled wire. Figure 2 shows a microscopy of the cross-section of a twisted pair eroded by a large PD activity; the abrasion near the contact point is clearly visible.

For building machines able to operate during a long lifetime, the windings made with standard enameled wires must be free of PD, despite the low-pressure environment.

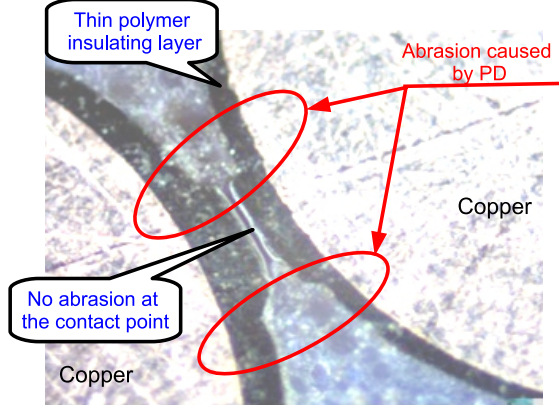


Fig. 2. Microscopy of the cross section of a twisted pair aged by a strong PD activity where the polymer layer abrasion is visible.

IV. PRINCIPLE OF THE PROPOSED IMPROVEMENT

In a motor coil, the outer surfaces of the wires are in contact together. Therefore, at a microscopic scale, an additional resistive layer deposited on each turn will create equipotential surfaces able to reduce strongly electric field in the air-voids between turns. Preliminary investigations are made on twisted pairs covered with a silver conducting paint. Fig. 3 shows the classical twisted pair on the left and the modified one with a conducting paint on the right.

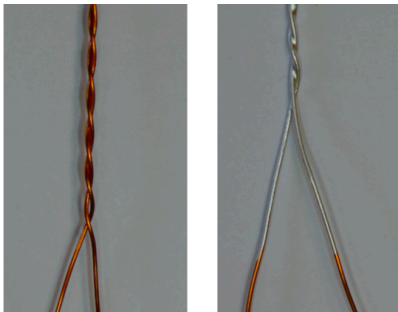


Fig. 3. Classical twisted pair (left); modified twisted pair (right).

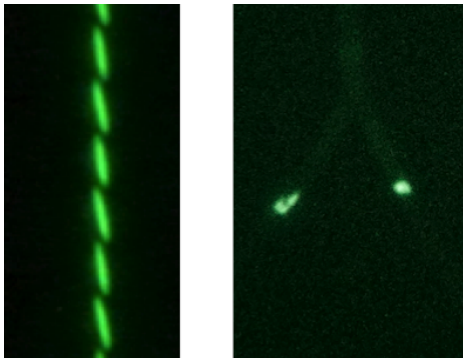


Fig. 4. DPs observed by a corona finder device (left standard twisted pair, right modified twisted pair with a silver conducting paint).

With the conducting paint, the electric field is concentrated in the thin PEI-PAI layer that has dielectric strength much higher than air. Figure 4 present an image of the PD activity of both twisted pairs fed by at $3kV_{peak}$ 50Hz. The pictures were made in a deep darkness with a night vision device called "CoronaFinder" [17] placed at 0.8m. This optical system is able to make a visible image from the UV and IR radiation emitted by the observed objects. For these pictures the voltage was much over the PDIV for getting many PDs. The left picture shows that PDs are distributed along the twisted pair; the right one shows that they are concentrated on the ends of the conducting paint layer. These pictures show that the conducting layer moves PDs to small zones. The abrasion is now localized in deterministic small areas rather than distributed along the twisted pair. However, electric measurements show a slightly lower PDIV for the modified twisted pair ($1.1kV_{peak}$ rather than $1.25kV_{peak}$). Therefore, at a given voltage over the PDIV, the abrasion due to PDs will be more intense. Without any corrective action, the enameled wire lifetime will be much lower.

V. ANALYSES OF THE ELECTRIC FIELD IN CRITICAL ZONES

A 2D finite-element (FE) linear 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 in the critical zone near the end of the silver conducting paint. Figure 5 shows the FE mesh of the electrostatic problem built at the micrometer scale. Figure 6 presents the corresponding color map of the electric field magnitude. The field is computed with a constant polymer relative permittivity of 4 and for 1kV imposed between the boundaries (conducting paint and copper wire). The simulation results can be applied with other voltages because of the linearity of the electrostatic problem.

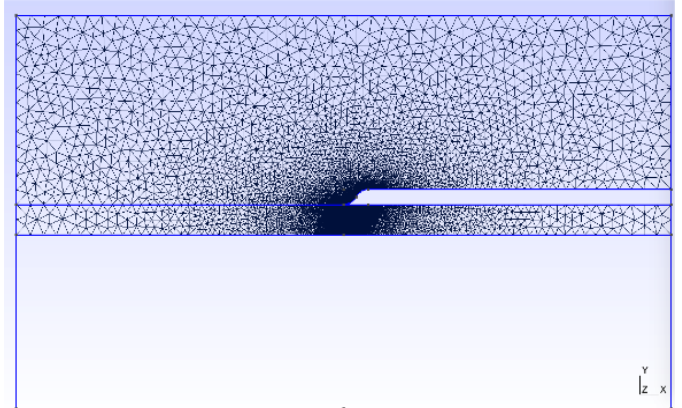


Fig. 5. Mesh of the critical zone and of the polymer layer.

In Fig. 6, the highest field values are removed because the sharp end of the conducting paint is not realistic. The field lines in the critical zone or air, where PDs may appear are plotted in figure 7. The global shape of these field lines is far from the straight lines on the uniform field of the Paschen's experiences. A deeper analysis must be made for applying his

results, reminding the hypothesis made by Paschen for interpreting these experiences.

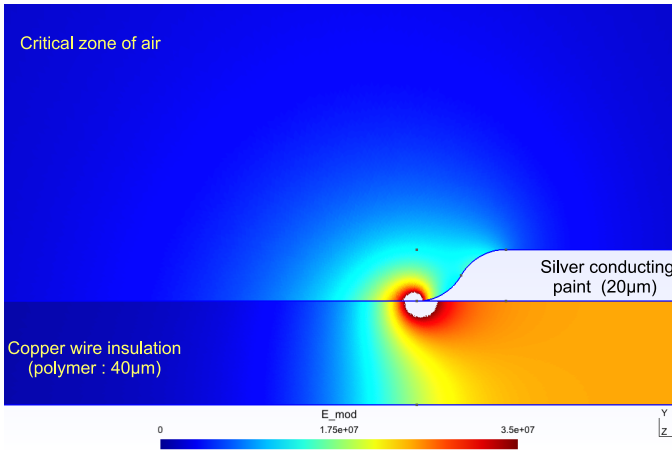


Fig. 6. Electric field in the critical zone of air and in the polymer insulation layer.

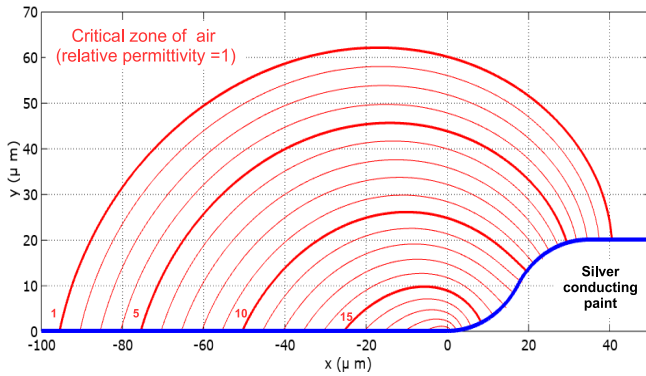


Fig. 7. Field lines in critical zone of air, near the end of the conducting paint.

VI. DISCUSSIONS ON PASCHEN'S HYPOTHESIS FOR PREDICTING THE PDIV IN A MOTOR WINDING

Let us remind that Paschen's works were made more than a century ago. At his time, the physics was mainly based on a corpuscular approach of free electrons accelerated by the Coulomb force $\vec{F} = q\vec{E}$. An electronic avalanche appears when the accelerated free electrons acquire enough energy for ionizing gas molecules when they collide. This electronic avalanche creates more complex phenomena corresponding to PDs or breakdown if no external phenomena stops the discharges. The PDIV corresponds to the electronic avalanche threshold. In Paschen's experiences, the free electrons were accelerated following the straight field lines the speed and the force are collinear vectors. The computation of the acquired kinetic energy is a scalar problem. At a field supposed exactly equal to the avalanche threshold, a collision of an accelerated free electron with a gas molecule absorbed the kinetic energy for creating a new free electron, which is accelerated by the Coulomb force. For a uniform field the free electrons follow the field lines. The trajectory of free electrons is superimposed to the field lines. The distance d between the flat electrodes is the field line length. However, for a non-

uniform field, the electrons inertia may change the free electron trajectories, they do not follow exactly the field lines. The computation of free electron energy is more complex because the free electron speed and the Coulomb force are no more collinear vectors.

The proposed analysis uses the Paschen's hypothesis but it adds the inertial equation of a mass m placed in a field force $\vec{F} = q\vec{E}$. The influence of the gravity is neglected. The mechanical problem is solved in an electric field map proportional to the electric field in the critical zone computed by the FE simulation at half the experimental PDIV of the modified twisted pair. This value is defined considering a perfect symmetry of the modified twisted pair: the same phenomena occur on each wire covered with a conduction paint. The air of the critical zone is supposed to be made only of nitrogen and oxygen.

The ionization energy of these molecules is 13.6 eV for Oxygen and 14.5 eV for Nitrogen. An average value rounded at 14eV is considered for defining the points where energy of a free electron is absorbed by an ionizing collision. The elastic collisions does not change free electron energies, they are not considered. The mechanical equation is solved with a very short time step of $0.01ps$; results are plotted in figure 8. Two voltages 550V and 183V (half the PDIV measured on modified twisted pairs and half the PDIV estimated at 10000m) are considered. This figure shows that the higher voltage create a stronger acceleration. The free electron needs a shorter time to reach the ionization energy level.

Figure 8 is plotted for a starting point of the first free electron at the beginning or line field 15 of Fig. 7. For another starting point situated at the beginning of a longer field line, the curves are similar but with weaker accelerations and longer times between two ionizing collisions because the field is lower but the mechanism is the same.

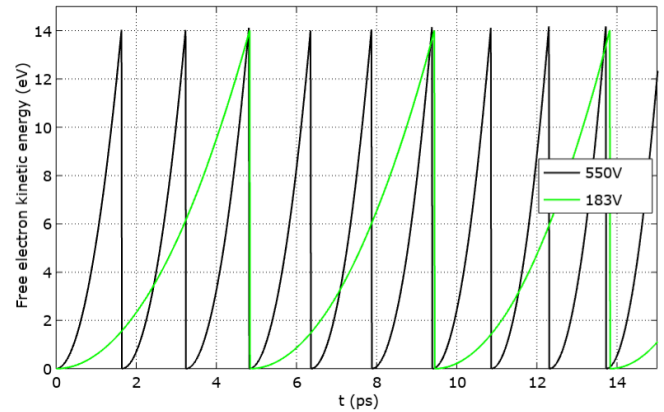


Fig. 8. Free electron energy between two ionizing collisions for line fields 15.

The trajectories of successive free electrons are plotted in figure 9 for 2 starting points corresponding to the field lines 10 and 15 in Fig. 7. The small circles added on the curves correspond to the position of free electrons when they get the ionizing energy for collisions. For computing these trajectories, a square mesh of $0.5\mu m$ is used. Figure 9 shows that, for this geometry and a voltage equal to half the PDIV at room temperature and pressure, the free electron trajectories (black lines) are very near the corresponding field line (red

lines). It is not exactly the case for a lower PDIV (green lines), where the distance between two successive ionizing collisions is larger. The trajectory and field line lengths are computed and compared in table 3.

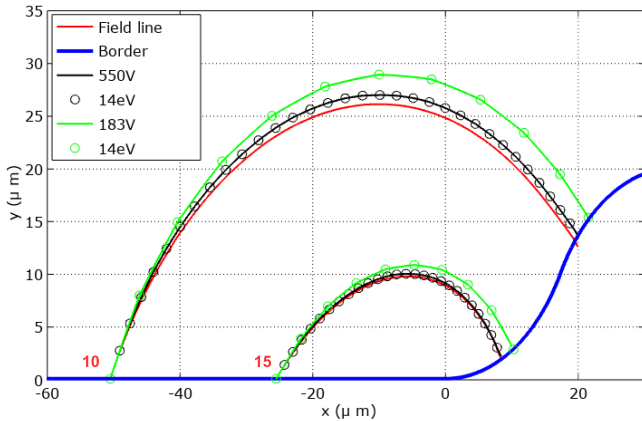


Fig. 9. Trajectories of free electrons and field lines 10 and 15.

TABLE 3. TRAJECTORIES AND FIELD LINE LENGTH COMPARISONS

Field line Nb.	Field line length (μm)	Tr.length at 550V (μm)	Difference (%)	Tr.length at 183V (μm)	Difference (%)
10	84.3	84.8	0.6	88	4.3
15	40	40	0	41	2.5

For lines length under 100μm of the considered geometry, the maximum error is more or less 5% when the field line length is considered rather than the actual free electrons trajectories. Therefore, Paschen end Peek theories can be applied for estimating the PDIV of modified motors up to an altitude of 10000m when the Paschen’s distance d is the field line length; the voltage is the potential difference between the ends of the considered line. More theoretical details are given in [14].

VII. INFLUENCE OF AN ADDITIONAL POLYMER DROP IN THE CRITICAL ZONE.

For getting higher PDIV with the modified twisted pairs, it is possible to add a drop on varnish in the critical zones. Figure 10 presents FE simulation results considering the same geometry with an additional varnish drop, which is represented in 2D by a circle arc, which radius is 40μm. The varnish relative permittivity is $\epsilon_r=4$. It can be seen that the higher field modulus is now inside the polymer drop; the critical zone in air is now shifted after the polymer drop, with another geometry and weaker fields. The corresponding field lines are plotted in Fig. 11; breaks at the border of the polymer drop are typical of the permittivity change.

The field line length in air and the corresponding potential differences are computed for both simulations and plotted in red on Paschen-Peek curves in figure 12. The “+” signs correspond to the FE simulation made without any polymer drop; the “o” signs are computed by the second simulation. The number placed near the signs corresponds to the field line ones.

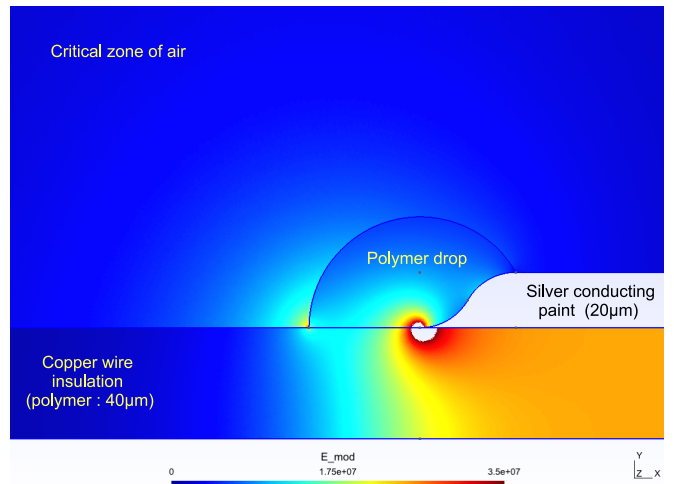


Fig. 10. Eclectic field modulus with an additional varnish drop.

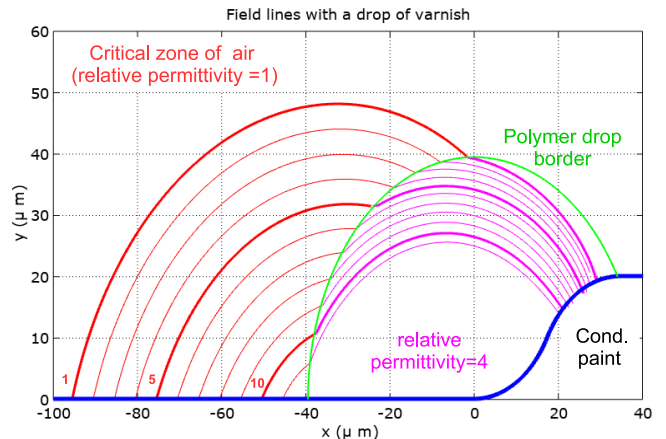


Fig. 11. Field lines in the critical zone of air and in the polymer drop.

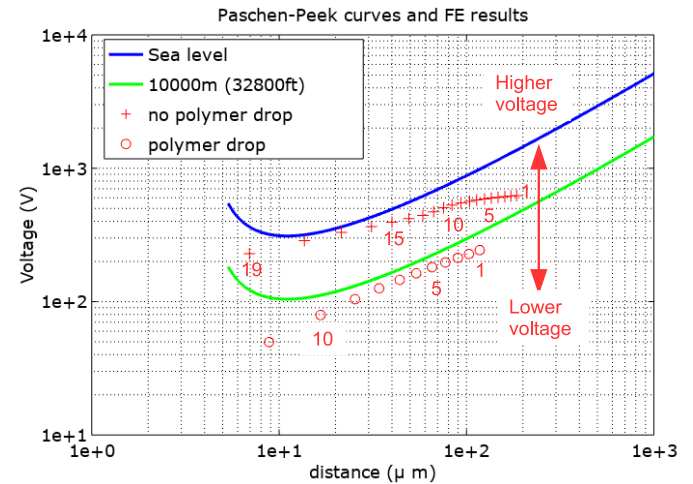


Fig. 12. PDIV estimation using Paschen and Peek theory and field-line length.

The “+” signs shows that lines 17 and 18 are very near the Paschen-Peek curves at sea level, the applied voltage is just below the PDIV at room temperature and pressure, which corresponds to the experimental measurement. With a slight increase of the peak voltage, PDs will appear between lines 17 and 18 for a distance between 15 and 22μm. At an altitude of 10000m, many PDs will appear but the physical problem is

more complex, Paschen-Peek theory cannot be used for studying them.

The positions of the “o” signs show a large security margin at sea level; it is smaller at 10000m. A small voltage increase will initiate PD; is a zone delimited by field lines 4 and 7 that correspond to much longer average distances of more or less 50 μ m.

VIII. CONCLUSION

A new approach for designing ac motor windings free of partial discharges (PD) is proposed. The method consists of adding a thin additional layer with a non-zero electric conductivity on the outer surface of the enameled wire used for making the machine winding. This additional layer reduces the electrical fields, in the residual air-voids existing between turns in motor windings. However, this additional layer moves the critical zones, where PDs may occur, in critical zones localized near the wire connections. With such deterministic localizations, it is possible to reduce strongly the PD activity by adding small quantities of varnish in the critical zones.

After studying the environment of electrical machines embedded in airliners, the influence of pressure and temperature on the PDIV is explained. Specific investigations on the proposed geometry places in the external environment of airliners show that the classical Paschen’s law modified by Peek can be used with an error of about 5%. On this basis, a simple 2D finite element is proposed for estimating the PDIV of the proposed solution in the harsh environment of an airliner.

The experimental investigations were made with a modified twisted pair covered by a silver conducting paint. It is not possible to build motor coils such a modified wire because its fragility its too high conductivity. Indeed, in a motor coil, the outer surfaces of wires in contact form short-circuited turns, which increase Joule losses due to currents induced by the variations on the magnetic flux. The proposed developments are at the beginning of the technological maturation process; investigations are in progress with thinner additional layers that have a lower conductivity in order to find a balance between the larger PDIV and the extra Joule losses.

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