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Banda Gnama Mbimbiangoye, Mallys Elliazar and Malec, David and Cambronne, Jean-Pascal *Partial discharge (DP) prevention within power converter busbars dedicated to hybrid aircraft propulsion.* (2021) . (Unpublished)

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1. Introduction

The postdoctoral position associated to this WP covered the period from January to December 2018. It was focused on the second aim of WP5, dedicated to better understanding of partial discharge inside power electronics converters designed for the future hybrid aircrafts expected to 2025/2035 period.

For this aim, many tasks were performed to achieve the free-charge objectives under DC electric field and power density increase requirements. Firstly, from WP2, a preliminary study based on various topologies of power busbars were analysed. In second, some simulation studies were performed to prevent them inside power electronics systems through a focalization on power busbars.

2. Context and problematic

The key expectations intended on this post-doc (O5) was the simulation/modelling studies of DP risk appearances within the busbars dedicated to the power converters and more widely within electrical insulating systems surrounding power electronics medias. This would run by:

- Providing information that can help to the design of connectors, busbars, power modules and cables, by minimizing PD risks;
- Assessing of electrical constraints minimizing the DP risks within the power converters as well as at the motor terminals;
- Studying the optimal conditions leading to the free-PD EIS under operating conditions.

3. Main results in stationary case

3.1. Topology and triple point

Figure 1 shows a view of the studied power converter topology on which this study is based. It consists in seven busbars slats (2 mm-thick) mounted between input bus capacitors and fly output capacitors. Electronic component ships are packaged inside power modules embedded in below. The DC bus is powered by a DC 2.5 kV input voltage. PTFE films are sandwiched between each busbars pairs. In such topology, many triple points appear in bus-bars/PTFE/air interfaces.

In power busbars application case, these triple point are the busbars-insulator-air junction point. De facto, the both confinement and power densities increasing expose electric insulation systems to more partial discharge risks. Added to materials defects (structural and chemical defects, electronic traps distributions, trapping level…), these partial discharge inceptions locally increase the electric field within the dielectric material. This local increase in electric field changes the intrinsic material properties and reliability, with the consequence of an irreversible insulators damage of dielectric that can affect the insulation system and then expose the power converters on which the propulsion depends on [1].

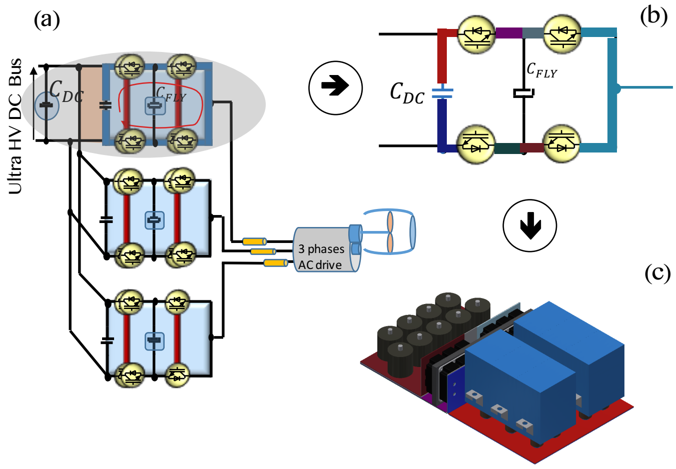

Fig. 1 : Power converter "FC-3 levels topology" model. (a) Structural view of converter, (b) Equivalent electric scheme by phase, (c) Designed packaging.

The triple point, corresponding to the one with greatest potential difference, is zoomed in Figure 1 (at the right). Since this point is the one submitted to highest electric stress, it is also the most exposed to partial discharge risk, as well for transient as steady state, especially during strong electrical stress during flight phases (take-off and landing). For this reason, the study focuses on the estimation of partial discharges risks through electric field assessment in this triple point to characterize the insulation behaviour of busbars for this applied electric specification. Based on simulation results highlighted around this triple point, partial discharge risks incurred on this one would also reveal those expected on other triple points, since other triple points support lower electric potential differences.

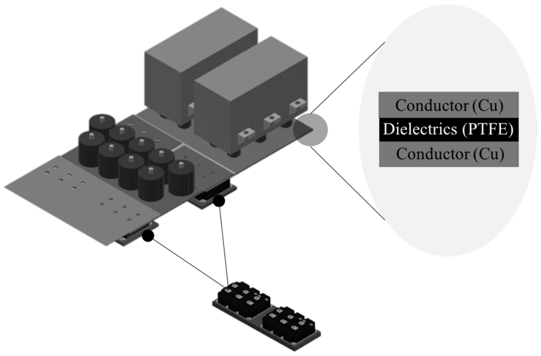

Fig. 2 : Schematic view of power busbars embedded inside a power electronics converter.

3.1. Simulation conditions

A common way to evaluate if partial discharges occur between two conductor materials consists in comparison of Paschen theoretical and experimental curves obtained in considered gas where Paschen's assumptions are applicable (uniformity of the electric field, plan/plan geometry of conductors, preponderance of electronic avalanche mechanism, ...) [2]. For air gaps greater than 1 mm (linear part of the Paschen curve), another alternative way would consist to assess the electric field distribution in a considered medium and to estimate the partial discharges risks by taking into ac-count the breakdown threshold in air. This last way is the one used in this study. Figure 3 shows a schematization of the considered calculation domain.

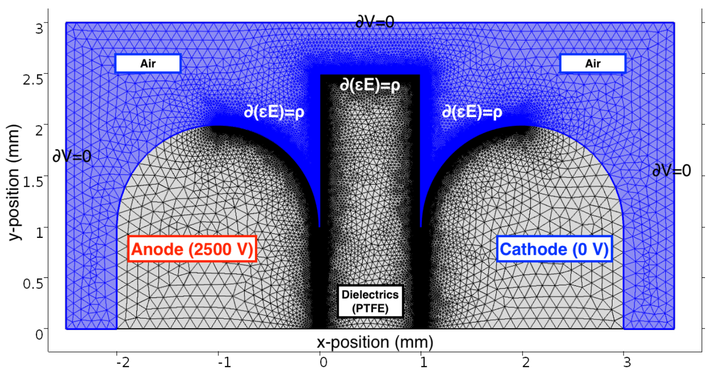

Fig. 3 : Calculation domain meshing for simulation studies.

The electric field is computed through finite elements method by solving Poisson's equation in both air and dielectrics domains:

$$\frac{\partial E(x,y)}{\partial x \partial y} = \frac{\rho(x,y)}{\varepsilon_0 \varepsilon_r} \qquad (1)$$

Where E is related to electric potential V such as :

$$E = -\nabla V \qquad (2)$$

ρ is the space charge density, ε_0 and ε_r the vacuum and relative permittivity, respectively. A zero flux was applied in air boundaries according to relation:

$$n \cdot (\varepsilon_0 \varepsilon_r E) = 0 \qquad (3)$$

Where n is surface unit vector. The calculation domain was non-uniformly meshed. To increase calculation precision of electric field and charge at the interfaces, refinement was added to both boundaries and in triple points as shown in Figure 3. The total meshing was sized in 7.5×10^5 finite elements.

3.2. Main Results

Simulated electric field due to gradual homocharges densities: Figure 4 shows the cartographies of simulated electric field obtained in the case of homocharges implantation near to dielectrics surface with charge densities ranging from 0 C/m3 to 1 C/m3.

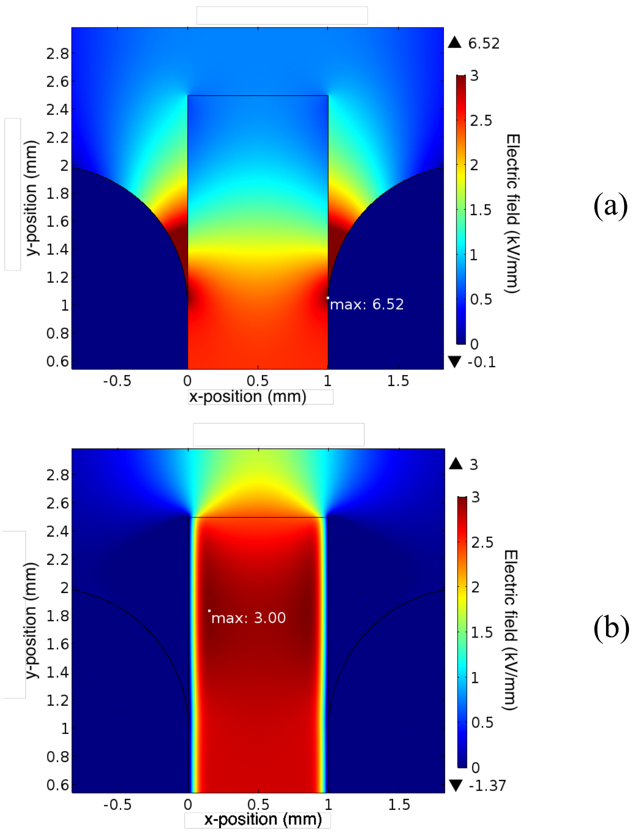

Fig. 4 : Simulated electric field at triple points under DC voltage. Stationary simulation. Absolute homocharges density of (a) 0 C/m^3, (b) 1 C/m^3.

These results highlight that more homocharges accumulation near dielectric surface seems to decrease electric field at the triple points (for densities greater than 1 C/m^3). As well for static implantation near busbars/insulator interfaces as for spatial ranging of their distribution inside insulator, accumulation of homocharges within insulating material sandwiched between busbars would qualitatively and quantitatively affects distribution electric field in the dielectric. It would seem that for a charge density below 0.5 C/m3, the electric field due to homocharges would not be sufficient to impact the total electric field in material and consequently at the triple points, although this threshold would not be the unique conditions to generate a partial discharge in air since other physical and electronic processes should also be met [3]. However, it appears that partial discharge risks would be attenuated with higher homocharges accumulation (above 0.5 C/m3) at insulators/busbars interfaces.

Simulated electric field due to gradual heterocharges densities: The same simulation, performed in same condition with heterocharges implantation give the reverse results such exposed in Figure 5.

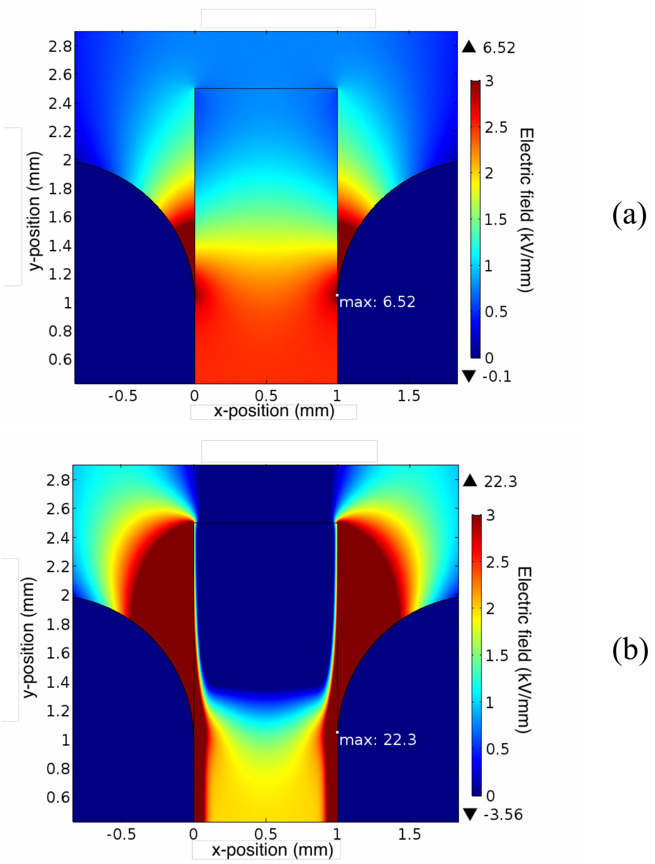

Fig. 5 : Simulated electric field at triple points under DC voltage. Stationary simulation. Absolute heterocharges density of (a) 0 C/m^3, (b) 1 C/m^3.

In presence of heterocharges close to the dielectric surface, the electric field rapidly grows in triple points and at dielectric surface. This increasing depends on charge density, while it decreases considerably in the volume of the insulator. This behaviour is the contrary of what observed with homocharges (Figure 4).

Various mechanisms could cause heterocharges accumulation in such solid insulating material polarized between busbars in a DC electric field. These heterocharges could be generated through natural traps within insulator, trapping distribution in dielectrics bulk, electrode/dielectrics interface defaults but also directly by extraction of charges towards busbars conductors due to a favourable internal electric field, chemical defaults or by detrapping processes induced by thermal activation through potential barrier. All these physical mechanisms that would make possible heterocharges accumulation would therefore be favourable to partial discharges inception in busbars environment [4, 5]. For this reason, although polarization in busbars configuration presented in this power circuit topology would not permit direct injection of heterocharges, prediction of their accumulation at busbar/insulator interface would require to carefully rethink industrial chain of insulators design dedicated to power converters intended to hybrid aircraft, in order to prevent partial discharge risks as highlighted by this study.

4. Time-dependent simulation of PD risks

Another part of these postdoctoral focused on simulation of PD-risks in time-dependent conditions. The main outputted results, based on generation and transport equations of charge mobility as function of electric field, reveal some difference in homocharge behaviour at insulator(PTFE)/conductor interfaces under DC electric field (cf. Figure 6).

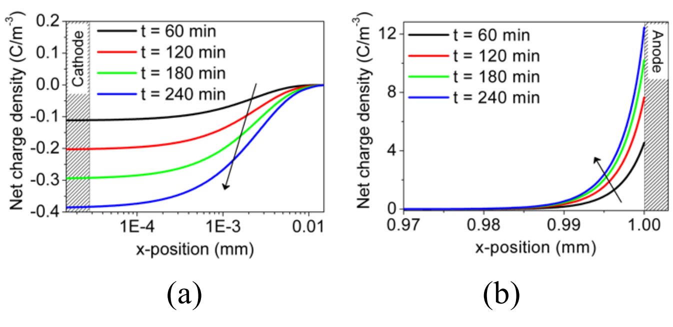

Figure 6. Net charge densities as a function of x-position within PTFE film in y = 1 mm (i.e.: at triple points level). (a) Negative charges arising from cathode electrode; (b) Positive charges arising from anode electrode.

By considering the net charge densities associated with total electric field (i.e.: net fluxes of mobile and trapped charges injected at the electrodes) we observe that more holes are injected/trapped at the anode and the injected/trapped electrons are dominant at the cathode. The electrons distribution is extended over approximately 10 µm while the holes distribution is extended over 2 µm. Quantitatively, the holes density injected from the anode, and trapped near the surface of the dielectric, is thirty times greater than electrons injected and trapped at the cathode.

Beyond 180 minutes, simulations seem to confirm the hypothesis of a very weak electron injection within the PTFE, for the electric field considered. The significant decrease of the electric field within the triple point positioned at the anode would confirm a progressive accumulation of holes injected at the anode. These positive charges, of the same sign as the applied voltage, form a homocharges area which will promote a reduction of the electric field at the PTFE/conductor interfaces. On the other hand, a very weak injection of negative charges at the cathode does not induce the creation of a large zone of negative homocharges. De facto, the electric field is less affected at the cathode triple point. These observations are in agreement with experimental ones that measure a larger injection of holes than electrons in PTFE films [6, 7], even for a highest DC electric field.

5. Conclusion

This reporting period through this postdoctoral position was efficiently used to develop some preventive tools in order to prevent the partial discharge risks within power busbars dedicated to hybrid aeronautical converter systems. Not only this study confirms that presence of space charges within a solid insulator generates an internal increase of electric field that impacts total electric field distribution, but it also highlights that for an applied electric field of 2.5 kV/mm, accumulation of small charges density in dielectrics (~ 0.01 C/m^3), induced by example by some chemical defaults, thermal, pressure or mechanical stress, would be sufficient to anticipate partial discharges in air surrounding power busbars dedicated to aircraft. Moreover, according to the sign of these charges, the risks of discharges would be differently appreciable. In case of homocharges accumulation at the busbars/insulator interfaces, electric field would tend to strengthen in dielectrics. This is less advantageously the case when these homocharges are transported in the volume of the dielectrics. On the contrary, heterocharges accumulation at busbar/insulator interfaces would reinforce the total electric field at insulator surface, leading to the greater risks of partial discharges resulting to the confinement of electric field at triple points. This situation would be accentuated as well by surface heterocharges density as their transport within the insulator bulk. Although PTFE is considered among the lower charging insulators, this study, applicable to other polymer insulators, reveals above all that charge accumulation of a few C/m3 would generate various mechanisms sufficient to age or activate degradation of insulators [4, 7].

In the intended case of hybrid-propulsion aircraft, electrical insulation system will be more exposed to partial discharge risks if insulation systems operate in thermal, humidity and pressure environmental conditions. In such condition, heterocharges accumulation would offer favourable conditions for partial discharges inception whose material, human and financial consequences could be irreversible. It is necessary to design non-charged insulation system in accordance to electrical strength intended for busbars to avoid any discharge inception. An alternative solution could be to screen busbars to ensure non-penetration of electric field in air gap, although this solution would increase weight density [8].

6. References

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