Numerical Investigation of Partial Electrical Discharge Occurrence in electric power system with Segmented Power Supply

N. Lanciotti, G. Galli, G. Krebs, O. Bethoux, E. Labouré, E. Odic

Université Paris-Saclay, CentraleSupélec, CNRS, Laboratoire de Génie Electrique et Electrotechnique de Paris, Gif-sur-Yvette, France
E-mail: noemi.lanciotti@centralesupelec.fr

***Résumé* — The transportation industry (automobile, aerospace) is undergoing a significant shift towards higher voltage supply, to increase embedded power. Increasing voltage might involve increasing partial discharge occurrence. In this study, partial discharges occurrence has been explored for conventional winding and high-coupled winding for Multi-Three-Phase Electric device based on CTAF (Chaîne de Traction à Alimentation Fractionnée). This innovative power supply concept has been presented in the Introduction section.**

According to the goal of this study, a 60-turns coil has been developed as the equivalent circuit and the lumped parameters have been determined by electrostatic and magnetostatic COMSOL simulation considering depending on frequency. The MATLAB/SIMULINK simulation of electric circuit has allowed the determination of voltage potential distribution. They injected as input on electrostatic COMSOL simulation to compute electric champ. Consequently, the maximum voltage supply without breakdown has been determined, for both studied cases.

I. INTRODUCTION

The aerospace industry is moving towards more electric aircraft (MEA), with the ultimate goal of achieving an all-electric aircraft (AEA) [1] for medium-haul and vertical take-off and landing aircraft . In this context, the aircraft architecture moves towards substituting hydraulic, pneumatic, and mechanical systems for advanced electrical components [2]. This drastic increase in electric power induces a tendency to increase standard voltages to limit Joule effect losses. In the aeronautics sector, this change towards higher voltage has significant specific consequences. Many previous studies assess the impact of high voltages. The present case investigates the possibility of partial electrical discharge occurrence ,tested through numerical simulations, on a classical structure of an electric machine (with or without a supply cable) and on a highly modular power traction chain structure.

To do this, occurrence conditions of electric discharges will be recalled and the higly modular power supply concept will be explained. The numerical methods will be presented and main results will be analyzed, giving some advancement perspectives.

I. CASE STUDY

A. Electric discharges

Electrical discharge occurs when a seed electron is accelerated by an applied electric field, gaining energy surpassing the ionization energy of gas atoms/molecules, resulting in an electron avalanche. Sources of seed electrons include cosmic rays, photo-ionization, and similar mechanisms. Assuming the presence of a seed electron, the conditions leading to an electron avalanche are elucidated by Paschen's Law, as shown in figure 1 [3-4]. Paschen's law is established for two infinite and parallel planar electrodes (homogeneous electric field).

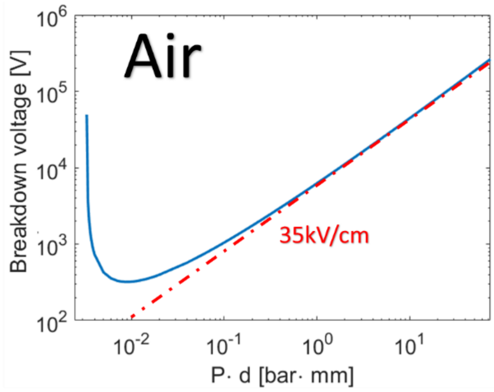

Fig. 1. Theoretical Paschen's curve in Air.

Moreover, the electrical components are subjected to a heterogeneous electric field rather than a homogeneous one, which enhances the likelihood of electrical discharge at low pressures. Furthermore, studies have demonstrated that, depending on the components within the electric drive, the Voltage Source Inverter (VSI) imposes transients that may induce up to three times the rated voltage at certain points of the electrical machine. This detrimental impact is mainly due to impedance mismatches and subsequent reflections in the cables connecting VSI with the electric machine [5].

The combined effect of voltage increase, low pressure at altitude (aircraft case), and overvoltages associated with the power electronics converters (i.e. VSI) underscore the interest in the numerical study presented in this article.

B. Electric Traction Chain with Segmented Power Supply

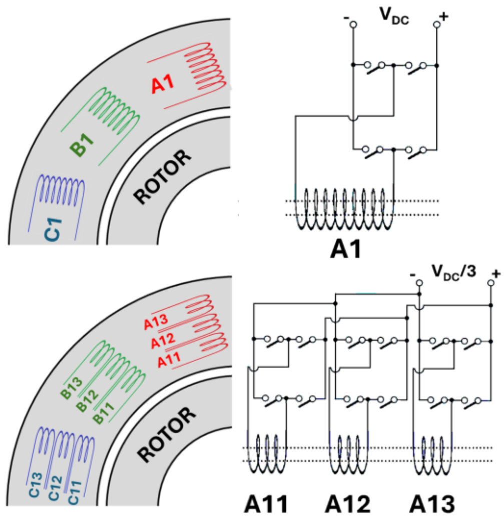

Fig. 2. Example of standard machine (at left) and Highly Modular Power Traction Chain (at right) [6].

This innovative concept, named CTAF for *Chaîne de Traction à Alimentation Fractionnée (i.e. Electric Traction Chain with Segmented Power Supply)* has been patented by the electrical engineering laboratories in Île-de- France

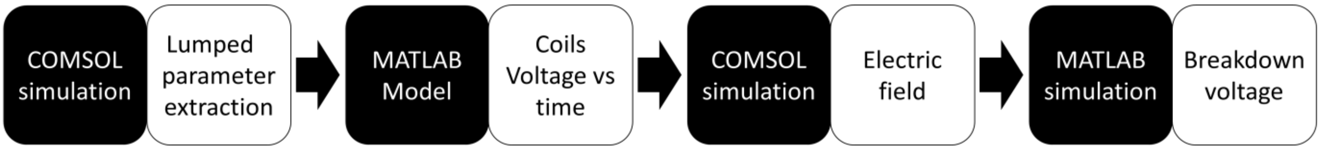

Fig. 3. Protocol of simulation study, which the blocks in black represent the software used and the blocks in white the output values.

(SATIE and GeePs) [6]. The core idea involves dividing the power supply coils of each phase in electrical machine into sub-coils controlled by individual power converters (VSI) with reduced power. As shown in figure 2, one phase coil winding on a tooth, characterized by N-turns, is divided in three sub-coils, each one characterized by N/3-turns. This new concept holds the promise of significant quantitative advancements in overcoming the challenges previously discussed, offering a remarkable degree of flexibility in voltage sizing. The present article exclusively focuses on the CTAF ability to achieve the same magnetic flux, in the electrical machine, by applying a lower voltage to each coil group when utilizing this novel setup. This studyconsiders a coil's division into three parts and thus the applied voltage.

II. NUMERICAL METHODE

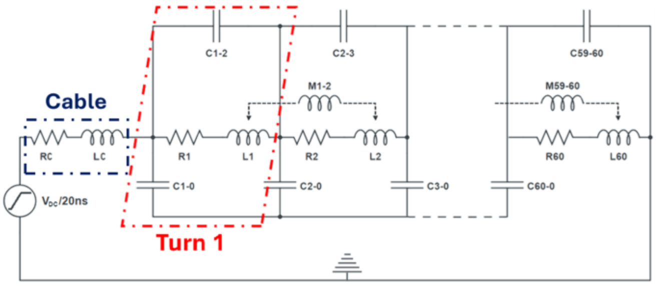

Fig.4. MATLAB model used to extract the voltage value for each turn as a function of the time (with or without cable power supply).

In simulation protocol (figure 3), a 60-turns coil has been implemented in the magnetostatic COMSOL simulation, from which the lumped parameters have been extracted and then they have been injected into the electric MATLAB model of the whole coil (Figure 4). From this, the voltages for each turn of the coil has been obtained, which has been re-injected into the electrostatic COMSOL simulation to obtain an electric potential map as a function of time (figure 5). Once an electric potential map has been obtained in the various explored configurations (presence or absence of the supply cable, fractional machine or not), the electric potential has been integrated over its distance at the most critical points for each case.

The threshold values for a discharge to occur in the different studied cases have been determined applying a multiplicative factor to the electric field found until to obtained a value of 35kV/cm. As mentioned, this one is the value at which, in air at atmospheric pressure, there is a high probability of obtaining a discharge.

III. RESULTS AND CONCLUSIONS

Tab. I. Maximum voltage supply (VDC) without breakdown.

Winding with supply cable (2m)	Winding without supply cable	Segmented winding
308V	560V	1643V

Figure 5 shows that due to the way the coil is wound, the first and last turns are positioned close to each other at the top, where the maximum potential difference is found. Table 1 provides the found values for the threshold voltage required to obtain an electrical discharge and clearly shows

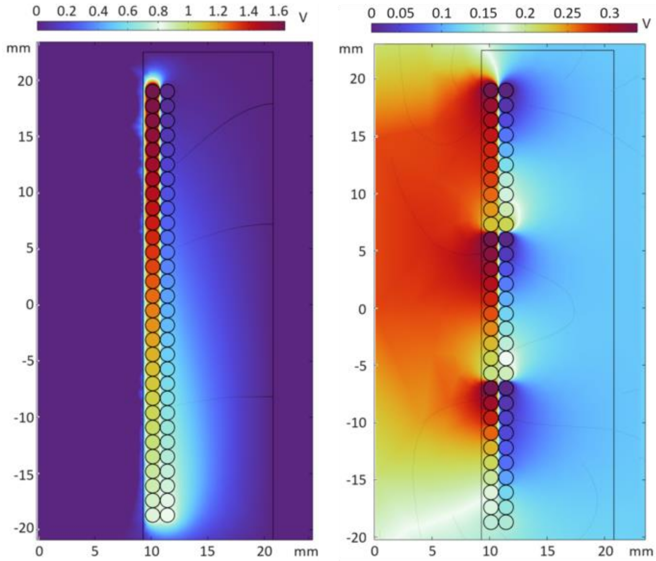

Fig. 5. Voltage distribution between turns of a coil. Standard coil powers with 1V (at right), segmented coil powers with 0.33V (at left).

how these values increase by eliminating the supply cable and even more by fractionating windings.

In addiction, our study reveals that lumped parameters exhibit a strong frequency dependency. Moreover, the presence of a supply cable amplifies the initial overvoltage, and the maximum voltage without breakdown depends significantly on the winding configuration. Notably, a high-modular winding solution eliminates the need for a supply cable, allowing the converter to be placed as close as possible to the winding.

While these conclusions appear promising, it is important to note that the numerical study of this problem is just the initial step, for this reason future work will involve setting up an electrostatic and magnetostatic coupled model, validating simulation results with experimental bench tests, and exploring the impact of power supply fractionation degree on the maximum voltage without breakdown. Additionally, we will explore the behavior of wound coil with hairpin and flat wire ones.

REFERENCES

[1] V. Madonna, P. Giangrande and M. Galea, "Electrical Power Generation in Aircraft: Review, Challenges, and Opportunities", *IEEE transactions on transportation electrification*, vol. 4, no. 3, 2018.

[2] L. Tom, M. Khowja, G. Vakil and C. Gerada, "Commercial Aircraft Electrification—Current State and Future Scope", *Energies*, 2021.

[3] G. Galli, H. Hamrita, C. Jammes, M. J. Kirkpatrick, E. Odic, et al.. "Characterization and Localization of Partial-Discharge-Induced Pulses in Fission Chambers Designed for Sodium-Cooled Fast Reactors", *IEEE Transactions on Nuclear Science*, 2018.

[4] J.M Meek and J. D. Craggs, "Electrical Breakdown of gases", Wiley, 1978.

[5] L. Benmamas, "Méthodes d'évaluation du risque de décharges partielles dans le bobinage de machines électriques destinées à la traction automobile", Energie électrique. Université Paris Saclay (COmUE), 2017. Français.

[6] H. Ben Ahmed et al., "Electric Traction Chain with Segmented Power Supply," 2021 23rd European Conference on Power Electronics and Applications (EPE'21 ECCE Europe), Ghent, Belgium, 2021.