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Partial discharge investigations in laminated busbars

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Abstract—The aim of the study is to predict the presence or absence of partial discharges (PDs), in a laminated busbar (LBB), for a given voltage. PDs appear in specific zones that are located using a representative sample of industrial LBBs. A numerical model based on Paschen's law, proposes an interpretation of the observed phenomena and an estimation of LBB Partial Discharge Inception Voltage (PDIV). A theoretical reasoning and simplifications, based on Paschen's theory, are proposed, for applying this well-known law in the case of non-uniform electric fields existing in LBB's.

Keywords—Laminated busbars (LBB); partial discharges (PD); triple junction area; Paschen's law, PDIV predictions.

I. INTRODUCTION

Laminated busbars (LBBs) are used in power electronic converters using basic or sophisticated structures [1, 2]. Specific designs are developed for high powers [3]. Nowadays, the insulated gate bipolar transistors (IGBT) are widely used and faster SiC components appear in the market. These electronic switches have short commutation times that create high di/dt in the electric circuit during transients [4]. The inductance L of the switching loop may produce large over-voltages $L di/dt$. Consequently, the design of LBBs used in the switching loops of converters must be made for getting inductances as small as possible. This goal is reached using flat conductors insulated by a thin polymer layer [5]. Combined with a general trend to operate with higher voltages, the electric field stress in the LBB insulating layers becomes a critical parameter of their design [6]. Therefore, a good knowledge of the mechanism of PD ignition in LBBs is becoming a major challenge because, when they exist, PDs cause local erosions of the polymer layer that reduce the LBB life times [7, 8].

In the current study, PDs location is explained using a representative sample of industrial LBBs. The paper proposes also a method able to predict the presence or absence of PDs in these areas, when the voltage increases. The suggested method is based on Paschen's law established from the electronic avalanche theory in gas and for uniform fields. The proposed 2D model is based on the actual geometry of LBBs. It shows that, for a voltage equal to PDIV measured at a standard pressure, Paschen's law can be used with a negligible error, by considering the field-line length in air rather than the inter-electrode distance. The proposed 2D model needs several simplifications. The forces on moving charges due to the magnetic field, which are perpendicular to the charge trajectories, are neglected. It is also supposed that PD ignition phenomena are much faster than electric transients in the converter. Therefore, the study is made considering a 2D

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model with a DC voltage equal to the actual maximum value of the converter transients.

II. EXAMPLE OF LBB USED IN A MOTOR DRIVE

The LBB makes the critical electric connections between components of power electronic converters of the switching loops situated between the electronic switches and the DC bus capacitors. Fig. 1 is an example of industrial motor drive that uses a LBB for connecting the rectifier, the DC bus capacitors and three IGBT modules. For the output connections, the inductance are not critical parameters, they are made with classical copper bars.

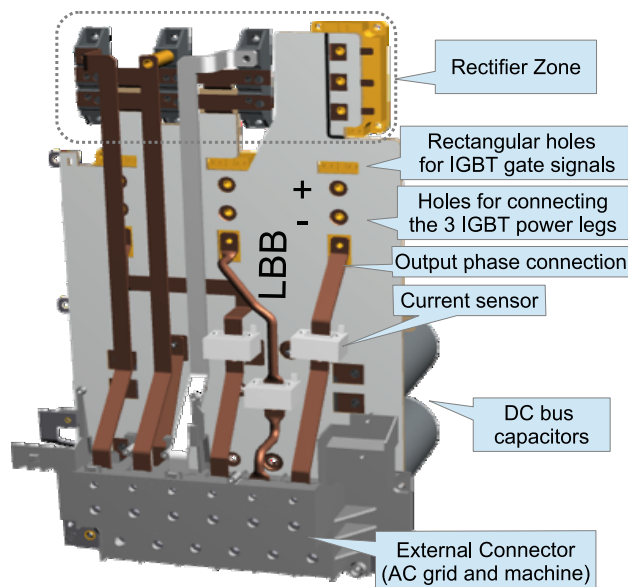


Fig. 1. Industrial motor drive made with a LBB in critical zones.

III. REPRESENTATIVE SAMPLE OF INDUSTRIAL LBBs

Experiments are made on representative samples of industrial LBBs (Fig. 2). These samples are made of two conducting nickel-plated copper plates of $1mm$ thickness. A $190\mu m$ polyethylene terephthalate (PET) layer provides the electrical insulation between the conducting plates. Two $20\mu m$ adhesive layers give the mechanical fixing. The standard thermal bonding process used for industrial LBBs is also used for the samples. Indeed, a suitable thermal cycle is applied under a strong pressure for eliminating the air bubbles in the adhesive layers. The polymer sheet is $5mm$ larger than the copper plates, for avoiding surface discharges between conducting plates on the sample sides, as it is performed for industrial LBBs.

When a high magnitude sine voltage is imposed between the two copper plates of a representative sample, PDs appear. For locating PDs on the samples, pictures were made in a deep darkness with a night vision device called "Corona Finder" [9]. This optical system makes a visible image from the UV radiation of PDs. Fig. 3 is representative of most of pictures made for voltages over the PDIV. The green zones show the UV radiation emitted by many PDs during the camera opening time. It can be seen that PDs occur only near the boundaries of the copper plates, in a zone called "triple junction area", where the ambient air is in contact with a conducting plate border and the insulating layer. In this area, the electric field in air is stronger than in polymer, due to its lower permittivity.

Fig. 3 shows that the emitted light is more intense on the bottom boundary, where the lower plate is present below the insulating layer. The geometry is not the same than on lateral sides, the electric field is stronger.

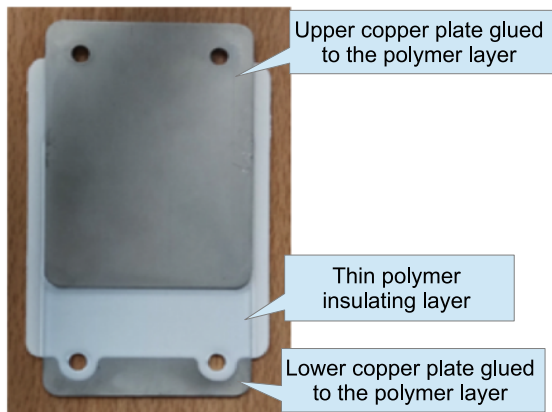


Fig. 2. Representative sample of industrial LBBs used for electrical tests.

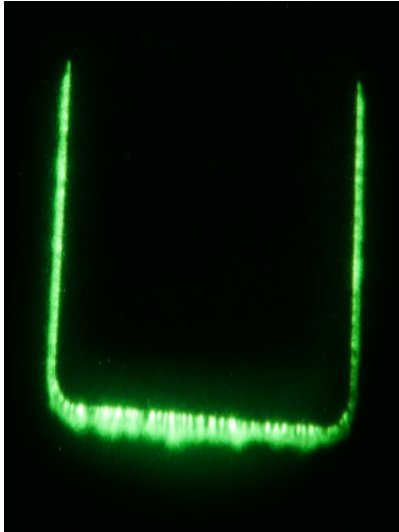


Fig. 3: Optical detection of PDs in the representative sample.

Microscopic observations are made on cutting planes perpendicular to the conducting flat surfaces, in areas where the lower conducting plate exists. The purpose is the determination of the triple junction area geometry at the micrometre-scale. Ten microscopies were made; Fig. 4 is representative of most of microscopies. Small differences are observed, but the typical shape of the triple junction area is a

vertical copper wall connected the horizontal polymer plane surface with a quarter-circle of $40\mu\text{m}$ radius. The punching process used for cutting the copper plates explains the conducting plates border shapes. During the manufacturing process, the orientation of the conducting plates is chosen according to the direction of the punching, to avoid sharp burrs in contact with the polymer thin film.

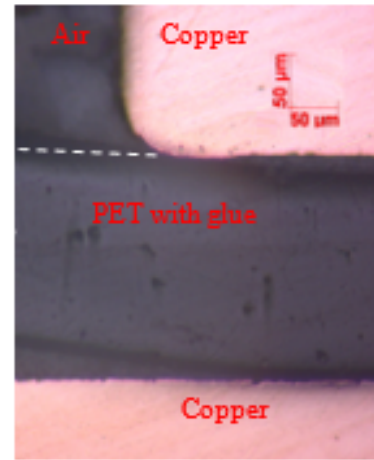


Fig. 4: Microscopic observation of a sample near the triple junction area.

IV. ELECTRIC FIELD IN THE TRIPLE JUNCTION AREA

The finite element method (FEM) is used for building a 2D model of the triple junction area with a dense mesh (Fig. 5). It computes the electric field when the copper plates impose the 2D problem boundary conditions, which are the electric DC potentials ($V = 1700\text{V}$ for the upper plate and $V = 0\text{V}$ for the lower one). Fig. 6 presents the electric field magnitude.

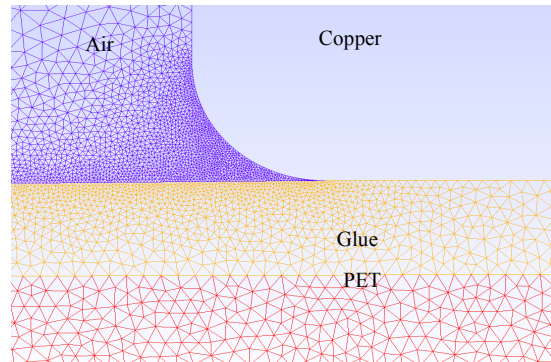


Fig. 5. FEM mesh of the triple junction area and the polymer layers.

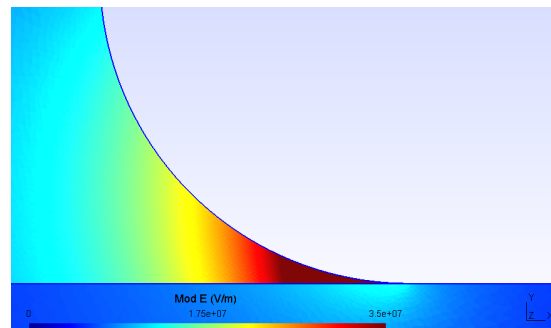


Fig. 6: Electric field magnitude in the triple junction area.

Fig. 7 shows 10 field lines in the triple junction area. Most of them are curvilinear, except the shorter ones that are close to straight-line segments. Consequently, the Paschen's law cannot be used in the triple junction area of LBBs, without additional hypotheses.

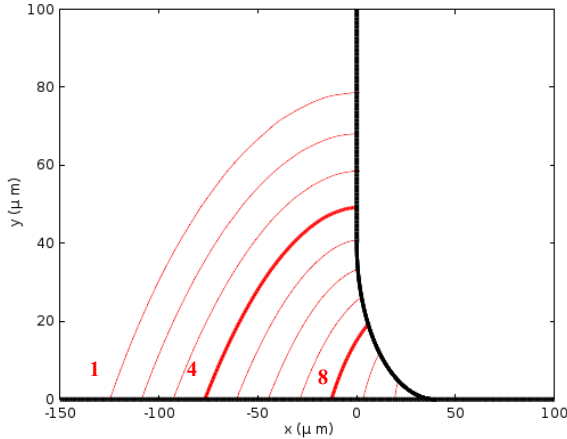


Fig. 7: Electric field lines in the Triple junction area.

V. ADDITIONAL THEORETICAL CONSIDERATIONS

For using Paschen's law, which defines the breakdown voltage in a gas as a function of the distance x pressure product, it is necessary to verify that the free electrons follow the lines as they do for the uniform fields of Paschen's experiences.

Let us remind that Paschen's works are based on Townsend's theory that considers that free electrons are accelerated by the uniform electric field between flat electrodes. If an accelerated free electron has enough kinetic energy when it collides a gas molecule, this latter is ionized and produced another free electron. This process initiates an electronic avalanche. This case corresponds to an external voltage slightly over the PDIV.

In the triple junction area of LBBs, the interesting parts of the field lines are situated in the air between the surface of the glue and the conducting plate border. Unlike Paschen's experiences, the inertia of electrons may have an influence on their trajectories. This difference with the general background of Paschen's experiences must be evaluated for determining whether it is negligible or not.

For igniting a PD in air, the energy acquired by a free electron must be high enough for ionizing a molecule of Oxygen or of Nitrogen. When the applied voltage is equal to the PDIV, it may be supposed that the collided gas molecule by a free electron absorbs the energy of the collision, by creating a new free electron, without any kinetic energy. This new electron is accelerated by the field and will collide another molecule, when it gets the ionization energy. The elastic collisions are not considered. With such simplifying hypotheses, it is possible to estimate trajectory of free electrons between collisions, by solving the mechanical equation of a solid object placed in the field force $\vec{F} = q\vec{E}$. The computation is made with the electric field map in the triple junction area, determined by the FEM model, for a voltage equal to the experimental value of the PDIV at room temperature and

standard pressure. Well-known values of electron charge and mass ($q = -1.602 \cdot 10^{-19} C$; $m = 9.11 \cdot 10^{-31} kg$) are used.

Figures 8 and 9 show the simulation results of the mechanical problem considering an example of a free electron appearing at the origin of the field line 4 in Fig. 7. The computation is made with a geometric square mesh grid of $0.4\mu m$ and a time step equal to $0.01ps$. The computations are made for two voltages: $1700V$ that corresponds to the PDIV measured at ground pressure and $850V$ that corresponds to the PDIV at a much lower pressure. In these figures, the small crosses correspond to the ionizing collisions with of a Nitrogen molecule, when the molecule absorbs the kinetic energy of the considered free electron for creating another one at zero speed.

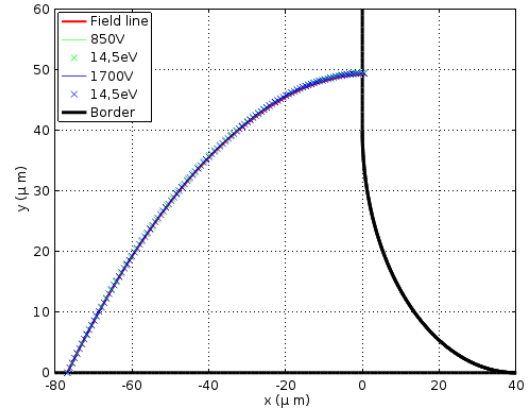


Fig. 8: Trajectories of free electrons between ionizing collisions for two voltages corresponding to PDIVs at two pressures.

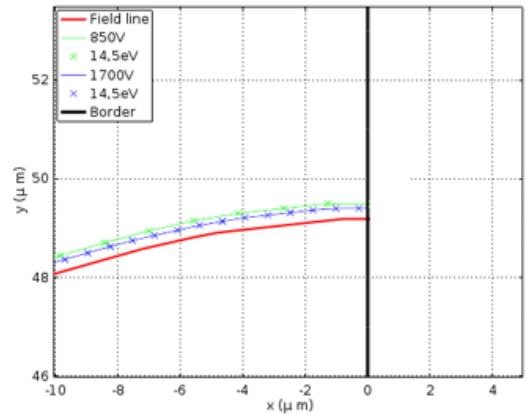


Fig. 9: Zoom of the ends of the curve of Fig. 8.

The results show that, for the field line 4, the free electron trajectories computed with these simplifying hypotheses follow the field lines. In Fig. 8, the curves are superimposed except at their very end. Additional simulations show negligible errors for the other field lines, for both pressures. It can be concluded that, in the triple junction areas of LBBs, the free electrons follow the field lines for a voltage equal to PDIV.

When a free electron is accelerated by the electric field over an infinitesimal distance dl by the Coulomb's force, it acquires an elementary energy:

$$dw = q|\vec{E}|dl \quad (1)$$

The relationship between electrostatic field vector \vec{E} , generated by scalar potential V is given as:

$$\vec{E} = -\vec{\nabla}.V \quad (2)$$

Considering a part of a field line between points a and b , (1) and (2) yield the energy accumulated by a free electron accelerated on the distance ab :

$$W = q \int_a^b \vec{E} \cdot d\vec{l} = q(V_b - V_a) \quad (3)$$

Expression (3) shows that the energy acquired by a free electron following a field line depends only on the potential difference between two points b and a of the field line. It does not depend on the magnitude variations of the electric field between the considered points. Consequently, Paschen's curves can be used for estimating the PDIV, when the distance between the parallel electrodes is substituted to the field line length, in the triple junction area of LBBs.

VI. PDIV PREDICTION BY USING PASCHEN'S CURVE

Paschen's law gives the breakdown voltage V_{br} in the gas between parallel conducting plates. Paschen used Townsend's model [10] that defines the second Townsend coefficient γ .

$$V_{br} = \frac{Bpd}{C + \ln(pd)}; \text{ with } C = \ln\left(\frac{A}{\ln\left(1 + \frac{1}{\gamma}\right)}\right) \quad (4)$$

In (4) p is the gas pressure, d the distance between the parallel electrodes of Paschen's experiences. The Paschen curve in Fig. 10 is computed with (4) and the well-known parameters for dry air at room temperature, taken in the literature [11]. The 10 red crosses correspond to the 10 field lines plotted in Fig. 7. For each cross, the length of the considered field line is the abscissa d and the potential difference between the end and the beginning of the considered line is the ordinate.

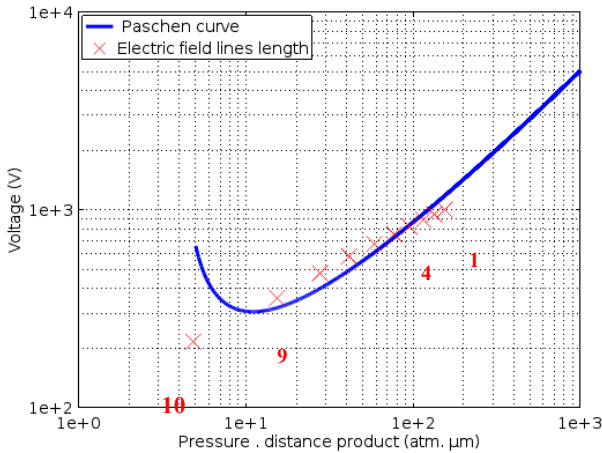


Fig. 10: Paschen curve and points corresponding to 10 field lines of fig 7.

The results presented in Fig. 10, show that PDs in the triple junction area appears for points over the Paschen's curve, between lines 4 and 9. For short field lines ($<10\mu\text{m}$), the free electrons do not acquire enough kinetic energy on the whole field length for ionizing a gas molecule. No PD appears very near the contact point, although the electric field is the highest. For long field lines ($>100\mu\text{m}$), the electric field magnitude is low and the acceleration of free electrons is not high enough for getting the required ionization energy. For lower voltages,

all the red crosses in Fig. 10 are moved downward and PDs disappear. For higher voltages all the red crosses are moved upward; PDs appear for longer field lines. Let us remind that the proposed 2D model is valid only for voltages close to the PDIV. The theory becomes much more complex for higher voltages corresponding to a permanent PD activity as in Fig. 3. Similar phenomena exist in triple junction area of other applications [12, 13].

VII. CONCLUSION

In industrial LBB made following the state-of-the-art rules, no significant air-voids exist inside the insulating layers. For voltages slightly over the PDIV, PDs occur in the triple junction areas, where the ambient air is in contact with the conducting plate borders and the polymer layers. The theoretical investigations show that, associated with a FEM simulation, the Paschen's law can be used for determining the PDIV. This analysis opens perspectives for designing high-performance LBBs able to work at higher voltages.

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