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# Laminated busbar PDIV improvement using a new varnish-based insulation technology with micro/nano fillers

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**Abstract**— Laminated Busbars (LBB) have proved to be the best solution for the design of power electronic devices operating at high power due to their low parasitic inductance and high current capabilities. As power electronic devices are becoming subjected to more and more severe operating conditions (due to electrification of aircrafts and SiC semiconductors development), innovative insulation solutions are needed to deal with Partial Discharges (PD) appearance in harsh conditions, like low pressure and high temperature. This paper presents a new varnish-based insulation technology as a low cost and more environmentally friendly solution for LBB insulation. Additionally, a theoretical study using electrostatic simulations backed with practical tests show different ways in which Partial Discharges Inception Voltage (PDIV) of a LBB sample can be improved using similar technologies like the addition of a certain quantity of varnish in critical areas. Furthermore, an investigation of further performance improvements using micro-nano fillers is presented. Such fillers include Alumina, Silica and hexagonal Boron Nitride. Improvements include high temperature resistance (up to 200°C), higher creepage distances and higher thermal conductivity.

**Keywords**—Partial discharge, varnish insulation, high temperature, laminated busbars, micro/nano fillers.

## I. INTRODUCTION

Laminated busbars (LBB) are the mechanical support and electrical connection used in power conversion circuits with high power ratings. They have been used for decades now instead of normal wiring or printed circuit boards because of their ability to carry high current densities, their compactness and their low parasitic inductance. The insulation technology used for LBB is based mostly on polymer films like PET, PI and PEN. The recent development of SiC semiconductor as well as the move towards More Electrical Aircrafts (MEA) [1][2], puts a lot of pressure on the proper design of LBB that can meet the new and more extreme operating condition requirements such as higher frequencies, low pressure and high temperature. The design strategy of LBB involves many criteria including PD and

stray inductance. The LBB must be PD free to insure the maximum lifecycle of the product because the presence of PD slowly degrades the insulation which eventually causes failure [3]. Stray inductance ( $L_{stray}$ ) must be as low as possible to reduce losses and voltage overshoot ( $V_{overshoot}$ ) levels during semiconductor switching due to current gradient ( $\frac{di}{dt}$ ) [4]:

$$V_{overshoot} = L_{stray} \frac{di}{dt} \quad (1)$$

Both of these criteria greatly influence the decision of insulation film thickness. On one hand, the higher the thickness the higher the PDIV is. But on the other hand, the lower the thickness the lower the LBB inductance is [4]. So there is a compromise to be made between the two criteria which makes LBB design very difficult for some applications [5]. Thus, there needs to be innovative insulation solutions that don't require high insulation thicknesses to ensure high PDIV.

Many previous works have contributed to a better understanding of PD in LBB. A comprehensive design strategy has been developed in [5]. Other PD-free LBB design works include [6] and [7]. Locating PD in LBB was demonstrated by in [8]. A FEM simulation model for PDIV prediction was developed by [9].

This paper aims to introduce a new varnish-based insulation for laminated busbar that could be used independently of traditional film-based insulation but could also be used as a complementary insulation with the aim to improve the PDIV while maintaining same film thickness and the same inductance.

## II. VIB TECHNOLOGY

### A. Description

Varnish Insulated Busbars (VIB) is an insulation technology derived from the same type of varnish used for the insulation of enameled wires for electrical machines. It has the benefit of being low-cost, and more environmentally friendly than film-

based insulation which require significant amounts of energy for the thermal presses required for the assembly of the LBB. VIB is still in its early development stages for full replacement of film insulation for certain applications. However, it can be used as a complementary solution to film insulation (III.B).

The formula of the resin has been adapted to LBBs. First, the main component which is the acrylic varnish is retained. It is chosen for its good resistance to temperature and its ability to be UV-cured as well as its good overall dielectric properties. Second, the plasticizing agent that helps with the flexibility of enameled wires was removed since the conductors of LBBs are flat and do not deform. Third, unlike enameled wire varnish, VIB does not use a solvent to lower the viscosity of the solution but instead uses a monomer thinner as to not emit harmful vapors during the manufacturing process. Lastly, a photo-initiator is used to allow UV curing and a Silane coupling agent is used as an adherence promoter as well as a dispersion agent in the case of incorporation of mineral fillers.



Fig. 1. Varnish Insulated Busbar (VIB) sample

### B. Manufacturing Processes

Sample manufacturing process is a repeating two-step process: A micro-spraying gun applies a very thin layer (5 to 10 $\mu$ m) of the varnish solution on the conductor then the layer is placed under UV light for a few seconds to be cured. The process is repeated multiple times until the aimed final total insulation thickness is achieved. The use of very thin layers is to not encapsulate air cavities large enough to initiate a partial discharge.

### C. Performances

The varnish has well known insulation properties and performances due to its long time use in enameled wire insulation.

The dielectric strength of the varnish is measured at 9.5 kV AC per 100 $\mu$ m. Like all solid dielectrics, this value can change with the overall thickness but the values are high enough for our use case. The acrylic varnish can also withstand high temperatures (up to 180 $^{\circ}$ C continuous) but it is limited by its overall thickness. This behavior is possible to improve with the incorporation of a Silane-type adhesion promoter and inorganic fillers such as Alumina (Al<sub>2</sub>O<sub>3</sub>) and Silica (SiO<sub>2</sub>).

The dielectric constant of the varnish solution was measured at 20 $^{\circ}$ C and 1kHz to be 3.2. Some recent studies show promise in the field grading method using dielectric constant gradients [10]. So, using fillers with high dielectric constant can potentially allow VIB to utilize the field grading methods in the future. Multiple fillers were tried for this purpose including alumina, Polyvinylidene fluoride, and barium titanate. The highest dielectric constant obtained at 1 kHz was 14 using 50%wt BaTiO<sub>3</sub>.



Fig. 2. Thermal withstanding improvement using 120  $\mu$ m layer of varnish filled with 2%wt of Silane and 10%wt of Silica (Right) compared to unfilled varnish (Left) at 200 $^{\circ}$ C after 8h.

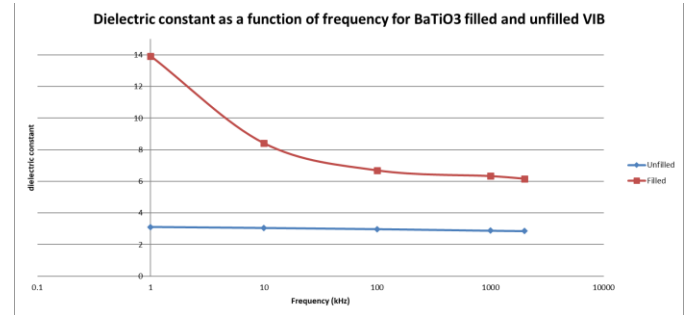


Fig. 3. Dielectric constant as a function of frequency for BaTiO<sub>3</sub> filled and unfilled varnish.

## III. ELECTROSTATIC SIMULATION

### A. Method

In order to properly understand PD behavior in laminated busbars, a simulation tool was developed. It is based on a three-step process to arrive at an estimated PDIV for a given configuration:

1) Solving the scalar potential formulation of a charge carrier free electrostatic problem using a finite-element solver

$$\text{div}(\epsilon * (-\text{grad } V)) = 0 \quad (2)$$

where  $V$  is the scalar potential and  $\epsilon$  is the dielectric constant. Using this formulation, insulating materials (air, thermo-glued polymer films, varnish) are characterized solely by their dielectric constant. The dielectric constant of our varnish was measured to be 3.2 at ambient temperature and 1kHz. The PET film used in the simulation has a dielectric constant of 3.25 and the glue used for assembly on both sides of the film has a dielectric constant of 2.7.

2) Calculation of electric field lines in the air

Unlike the vector potential formulation, the scalar potential formulation does not give the electric field lines directly. They must be constructed numerically. A modified Whittaker ballistic method [11] is used for this purpose. The algorithm first looks for the high electric field segments at the limits of the mesh representing the air. Then, it constructs the field line using a series of small segments, one for each mesh element, all parallel to the electric field direction within said element.

### 3) Comparison with Paschen's curve

The most widely acknowledged law regarding PDIV of air in a uniformly distributed electric field is the Paschen's curve which is an expression of the breakdown voltage between two electrodes in a gas as a function of pressure and gap length:

$$V_d = \frac{B \cdot p \cdot d}{\ln(A \cdot p \cdot d) - \ln\left(\ln\left(1 + \frac{1}{\gamma_{se}}\right)\right)} \quad (3)$$

where  $V_d$  is the breakdown voltage in volts,  $p$  is the pressure (atm),  $d$  is the gap distance (m),  $\gamma_{se}$  is the secondary-electron-emission coefficient (the number of secondary electrons emitted per incoming positive ion),  $A$  and  $B$  are constants for a given  $E/p$  ratio ( $E$  is the electric field).

It has been successfully used to model the PDIV in LBB in [9]. So, once all field lines in the air are calculated. For each field line, its length and potential difference across it are stored as datapoints and plotted with the Paschen curve. If none of the datapoints are above the Paschen curve, there would be no PD theoretically. In this context, the PDIV is, by definition, the input voltage necessary to generate field line datapoints that intersect with the Paschen curve at exactly one point while all other datapoints are below the Paschen curve. In order to obtain the theoretical PDIV for a given configuration, an iterative numerical method is employed to arrive at this value.

### B. Proposed solution

While VIB is capable of being used as a replacement of traditional film-based insulation for LBB, it is still in its early validation stages. A more immediate use case is a complementary insulation to in the triple junction areas of film-insulated LBB.

Figure 4(a) shows the cross section of the LBB samples (two 1mm thick conductors with one 230 $\mu$ m PET insulation film) with no varnish. The simulation results show, as expected, a very high electric field concentration in the triple junction area where air is present. Figure 5(b) Shows the simulation results with the introduction of varnish insulation in the triple junction area. This has the effect of making sure the intense electric field is inside the dielectric and not in the air. Since our simulation tool only constructs field lines in the air, it gives much higher PDIV values. At 20°C, the projected improvement according simulations is from 730V up to 2.2kV depending on the added varnish quantity.

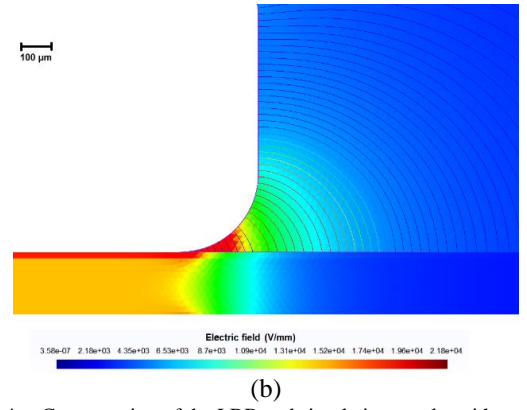
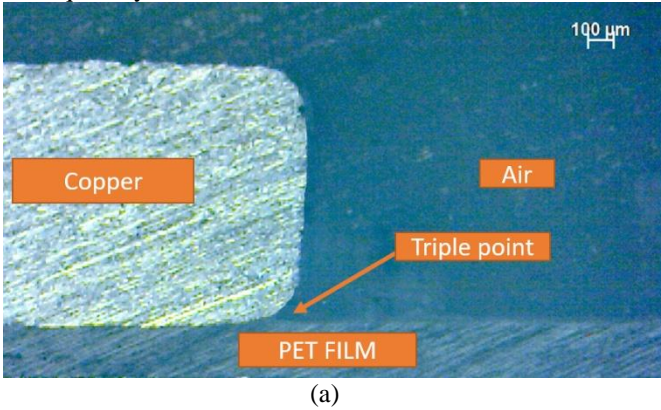


Fig. 4. Cross-section of the LBB and simulation results without any varnish in the triple junction area

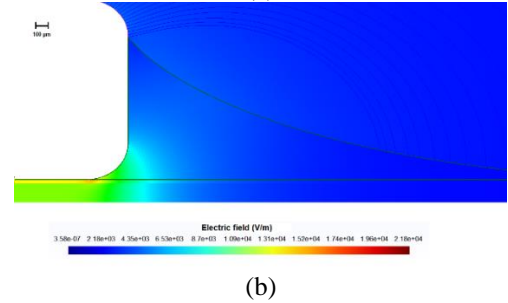
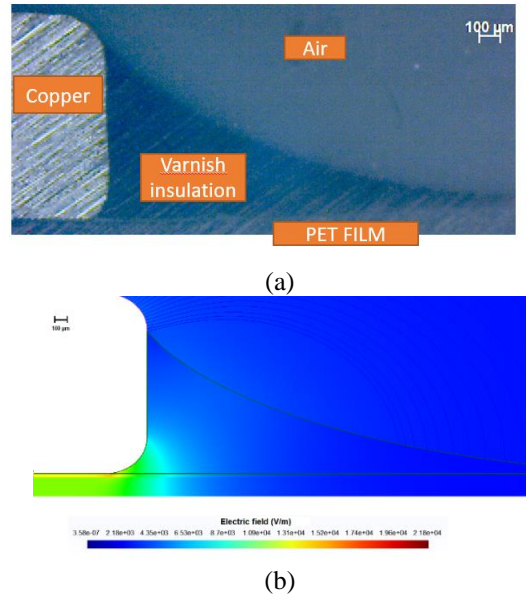


Fig. 5. Cross-section of the LBB and simulation results with varnish in the triple junction area

## IV. EXPERIMENTAL RESULTS

To confirm the PDIV improvement suggested by the simulation, ten LBB samples were prepared. The parallel capacitance as well as PDIV measurement at room temperature showed close values for all of them which is to say they are close to identical. Five of these samples were then used to apply varnish in the triple junction areas and PDIV was measured again.

There is a significant disparity between the varnish reinforced samples as can be seen in the standard deviation of the data in figure 6. This can be attributed to the lack of accuracy of control for the varnish thickness using our method. So, some samples end up with more varnish reinforcement than others. This also potentially explains the higher PDIV gain compared to projected values from the simulations.

The slight decrease of PDIV with temperature can be attributed to thermal agitation of air molecules increasing molecule and electron displacements (higher kinetic energy).



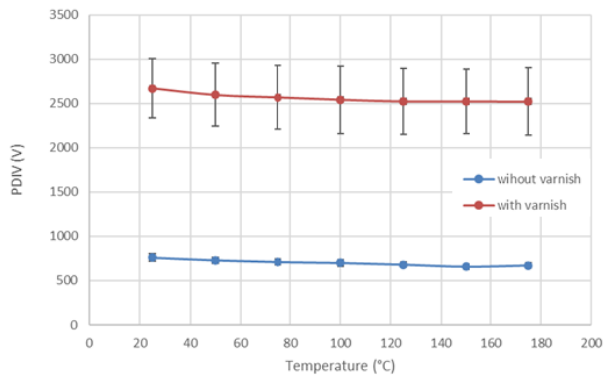


Fig. 6. PDIV vs temperature for LBB samples with and without additional varnish insulation in the triple junction areas.

This causes the Townsend discharge to be initiated sooner (at lower voltage levels). Temperature also effects the dielectric constant of the insulating materials which can change electric field distribution and create higher electric field intensity in the critical areas.

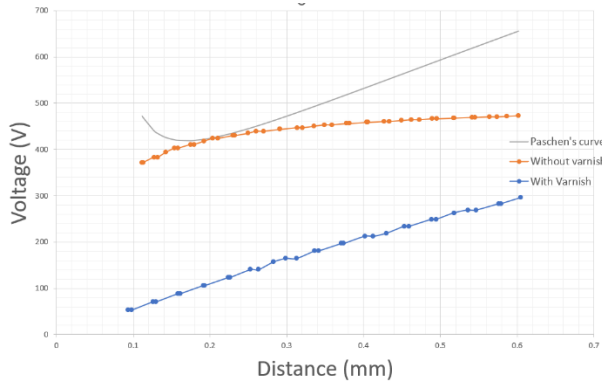


Fig. 7. PDIV vs temperature for LBB samples with and without additional varnish insulation in the triple junction areas.

Figure 7 gives the theoretical explanation for the increase in PDIV with the addition of varnish insulation. The program only constructs field lines in the air. Without varnish, these field lines are at the triple point where the electric field is most intense. So, the voltage drop across these field lines is very high which causes them to intersect with Paschen's curve and initiating PD. With varnish, the intense electric field is not only reduced but is also contained within an insulator with a high dielectric strength. So, the air, where the field lines are constructed, now has much lower electric field intensity and consequently lower voltage drops across the field lines well below Paschen's curve. Therefore, the PDIV is much higher.

## V. CONCLUSION

The VIB technology is a promising insulation solution for high voltage applications due to its low cost and low environmental impact. It is also a flexible technology thanks to the possibility of adding different types of fillers to modify or improve some of its characteristics such thermal conductivity, dielectric constant, temperature resistance. Thanks to simulation tools, a better understanding of PDIV behavior with regards to different factors is achieved and allows for the exploration of different potential solution for PDIV improvement. One immediate potential solution and use case for the VIB

technology is the addition of varnish in the triple junction areas in film-insulated laminated busbars where PDIV can be improved significantly even at high temperature while keeping costs down as well as overall compacity and low parasitic inductance.

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