Investigation of Electrical Stress in High Voltage IGBT Power Module Using Finite Element Simulations

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Abstract — With increase in the demand for electrical power conversion and control, new power electronic technologies are being developed rapidly. The power conversion is possible because of silicon power devices which are the most important components of any power electronic system. Among the power devices, insulated gate bipolar transistors (IGBT) are more accepted and widely used in various applications. The blocking voltage rating of the IGBT has increased up to 6.5kV which has resulted in higher demand on the partial discharge and insulation resistance of the insulating material. The use of IGBT module in high voltage applications can develop high electric field strength at the junction of silicone gel, substrate and the metallization. This high field may create an electric discharge known as partial discharge in the silicone gel if there is any flaw like protrusion at this location, which gradually results into the failure of the IGBT module. In this paper, the high electric field is localized and its value is found using finite element analysis of IGBT module, with protrusion and without any flaw, according to IEC 61287 standard. Index Terms—Electric field, IGBT power module, Partial discharge

I. INTRODUCTION

The voltage rating of the IGBT module has reached up to 6.5kV [1] because of the developments in the high voltage high power applications of power electronics which arises the problems related to electric field insulation in the high power IGBT modules. The high value of electric field is critical for the life of dielectric gels used in the power module because it creates the electric field reinforcement and partial discharge problems, leading to the breakdown of the insulation material commonly used in the power module.

To study this electric field reinforcement and partial discharge problem, a prototype can be developed. But this process is time consuming and the prototype may not meet the actual requirements. Also it is not easy to change the various parameters and modify the prototype for different conditions. The measurement of electric field is complicated and tricky process. Hence the better option is the Finite Element Methods which are used successfully for the electric field analysis. Using finite element simulation software we can localize the high electric field in the different parts of the IGBT module.

In this paper, the location of highest electric field in IGBT power module is found using the finite element simulation. Any defect at this location will create field reinforcement and partial discharge. The same defect in other part would not have such critical effect. The results can be validated with the electroluminescence analysis given in [3, 6] according to IEC 61287 standard [2].

II. PARTIAL DISCHARGE AND INSULATION FAILURE

Fig. 1 shows the cross sectional representation of the IGBT power module. The insulating substrate provides support to the power module circuitry. The silicon chips (IGBT and diode) are soldered on the copper metallization of the ceramic substrate. Generally metallization can be done in two ways: DBC (Direct Bonded Copper) or AMB (Active Metal Bond). Al₂O₃ (Alumina) or AlN (Aluminum Nitride) is generally used as the substrate ceramic material. They provide good electrical insulation between the high voltage switching chips brazed on them and the grounded heat sink. They also provide good thermal conductivity. The substrate is soldered on a base plate made of copper or AlSiC, which provides mechanical support for the insulating substrate and transfers the heat from insulating substrate to the heat sink because of its high thermal conductivity.

![Fig. 1. Schematic representation of IGBT module cross-section [9]](image-url)
This whole structure is covered by a soft encapsulant, known as silicone gel. It provides insulation protection between conducting parts against high voltage levels and prevents partial discharge. It also protects the chip and other metallic components from environmental conditions such as moisture, chemical etc. The chip terminals are connected using Aluminum wire bonding. External terminals are brazed on the metallization of ceramic substrates. This whole assembly is protected by plastic case.

Fig. 1 shows that the IGBT power module consist of a stack of dielectric materials subjected to high voltage. If these insulating materials contain any voids or other flaws in their bulks, partial discharge may occur. It can propagate and develop into electrical trees. It increases the temperature, produces mechanical erosion and leads to gas formation reducing the life of dielectric material. This progressive degradation of the dielectric material under electrical stress due to partial discharge causes the breakdown of the insulation.

Electroluminescence can be seen before the inception of partial discharge and electrical treeing in the areas of insulating material where electrical field is high. The high electric field excites the molecules within the gel which emits the light during relaxation. This light emission is considered as a pre-cursor for partial discharge [3]. We can validate the location of high electric field found in simulation using the location of electroluminescence.

The dielectric materials subjected to voltages greater than 1.5 kV must satisfy resistance to the insulation and partial-discharge requirements and they must be tested for the same [4, 2]. The IEC (International Electrotechnical Commission) standard provides such test method to check the insulation and partial discharge resistance of the dielectric material. IEC 61287 standard is commonly used for IGBT module [2, 4]. Fig. 2 shows the test time and voltage for insulation and partial discharge test according to this standard. The electric insulation test is carried out at the voltage given by following equation for one minute.

\[
U_{prms} = \frac{2U_m}{\sqrt{2}} + 1000V \quad (1)
\]

Where \(U_m\) is the maximum permissible blocking voltage of the IGBT power module. This test is performed by short circuiting the external connections (Emitter, Collector and Gate) and applying the high voltage between the shorted connections and the base plate. If no insulation breakdown occurs then this test is passed. For 6.5kV IGBT module, the insulation test is performed at around 10.5kV RMS voltage and if it is passed, partial discharge test is conducted.

For partial discharge testing 1.5 times the \(U_m\) RMS voltage is applied for one minute and after that the 1.1 times the \(U_m\) RMS voltage is applied for 30 sec. The partial discharge is measured at the last 5 sec of the test cycle. To pass the test, the measured value of partial discharge must be below the 10 pC. The frequency of the voltage is kept 50 or 60 Hz during this test. The partial discharge measurement voltage for the 6.5 kV IGBT module according to this cycle is 5kV RMS. The partial discharge which occurs in the first 60 sec of the test cycle must be removed in the last 30 sec.

**III. ELECTRIC FIELD SIMULATIONS USING FINITE ELEMENT ANALYSIS METHOD**

The test method given in the IEC 61287 standard provides the value of the partial discharge but not the location of the partial discharge. The location can be decided by the optical detection system which detects electroluminescence at the areas having high electric field, but it is not possible to measure electric field directly inside the IGBT module. If the geometry is modified to measure its value, the measured result would be incorrect as the field repartition is changed. Hence the finite element simulations are used to localize and find the value of high electric field in the IGBT power module which is the main cause of the partial discharge problem. Various multiphysics simulation softwares are available with such capability. In this section such simulations of IGBT power module are presented.

**A. Electric Field Simulation of the module without any imperfection**

In this part, the geometry and the dielectric material of the IGBT module is considered without any flaw. All the simulations are done according to real dimensions of the IGBT module stack. The voltage is applied according to IEC 61287 standard on the top metallization while the base plate is connected to the ground. The value of this voltage is taken as 5kV RMS corresponding to the partial discharge test voltage of the 6.5kV IGBT module.
As the dielectric constant and the resistivity of the dielectric material directly act on the voltage repartition, they are taken into account in all the models made for the simulation [7]. The dielectric constant of ceramic substrate is taken as 8.9 and the resistivity is taken greater than $10^{12} \, \Omega\cdot\text{m}$. The value of dielectric constant for the silicone gel is taken as 2.85 and the value of resistivity is taken as $10^{13} \, \Omega\cdot\text{m}$ [3]. The AlN ceramic substrate of standard thickness 0.63mm (blocking capacity 13kV) is used for all the simulations [8, 4]. The thickness for the metallization is 300µm in all the simulation models [4].

Fig. 4 shows the simulation result of the IGBT module considering no imperfection in geometry and material. It shows considerable field reinforcement at the edge of the metallization. The highest field is found at the corner of the metallization due to the sharp edge of the metallization where gel, substrate and metallization are connected. The maximum electric field value obtained in this case is about 44.6kV/mm for a 5kV RMS voltage applied as shown in Fig. 4. The optical localization test given in [3, 6] shows the electroluminescence and partial discharge at the same location inside the IGBT module. Hence the simulation results are validated.

B. Electric Field Simulations considering protrusion at the metallization base

During the metallization process when copper is brazed onto the surface of the substrate, some braze may protrude below the metallization which forms a very sharp edge at the metallization corner [10]. At this corner of the copper metallization, the electric field is high and the partial discharge primarily occurs there [6]. Hence the formation of protrusion at this location increases the electric field to very high value. Fig 5 and 7 shows simulation models of the AlN substrate with active metal brazed metallization having a protrusion.
To show that the electric field is very high if the protrusion is sharp, the simulations are done for two types of protrusions; one for flat ended protrusion and other for circular ended protrusion. In the simulation model of flat ended protrusion, as shown in Figure 5, the length of the protrusion is 20µm and the diameter is 5µm. The field distribution for this model is shown in Fig. 6. It shows that the maximum electric field inside the gel is $164 \times 10^9$ kV/mm at the protrusion tip. Hence the module having such protrusion at the metallization would likely fail the partial discharge test.

Fig. 7 shows the model with circular ended protrusion. In this model the length of the protrusion is 20µm and the diameter is 5µm. The diameter of the circular end is 5µm. The simulation result shows that the maximum electric field is 663kV/mm and it is found at the protrusion tip (Fig. 8). This shows that with sharpness of the protrusion, the value of the field reinforcement increases. The module with such protrusion may fail the partial discharge test as the electric field inside gel is much higher than the reported field strength of silicone gel.

IV. CONCLUSIONS

FEM simulations show that the electric field is high at the metallization corner where ceramic substrate, silicone gel and copper metallization are bonded. If there is any manufacturing defect like protrusion at the metallization edge, it increases the electric field value. This high field can be resulted in to partial discharge problem and progressively it decreases the life of the insulating material.

Finite element simulations are very useful in localizing and determining the high electric field values where direct access to that location is not possible. Using these simulation results the solutions to minimize the value of high electric field can be develop and implemented during the design stage.

REFERENCES