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Enhancing voltage rating of standard power modules for harsh environment applications

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Abstract

Recent advances in wide band-gap semiconductors technologies enable an increase in the power density of converters. The advantages of silicon carbide (SiC) devices are well documented and packaging solutions for high voltage components (6.5 – 10 kV) are available. However, when insulation coordination constraints are considered, isolation distances become a major issue, as they result in larger packages. In this paper, we describe and demonstrate a simple solution which allows to extend the capability of a standard power module package to higher voltages.

1 Introduction

Wide band-gap semiconductors are widely used for power conversion and are a core-technology for medium voltage power conversion and high voltage direct current (HVDC) power transmission. For these latter applications, power modules must offer high power density, while withstanding high voltage stress. Current research tends to get the best compromise between electrical insulation performance and compactness, by adjusting the geometry [1], [2], the design [3] or by material processing [4], [5].

For higher voltages (6.5 kV and more), the external surface of the power modules must be considered carefully: the voltage ratings of a package are dictated by clearance and creepage distances, as defined in IEC standards [6]. Creepage distances (the distance between two conductors along a solid insulating surface) are set by the geometry of the package, the class of its material, and the level of environmental pollution.

Regarding the geometry of the package, an open standard has been introduced for power modules [7], [8], with a maximum voltage rating of 6.5 kV. An example of its implementation is Mitsubishi's IGBT Dual type X-series HV100 power module (Fig. 1).

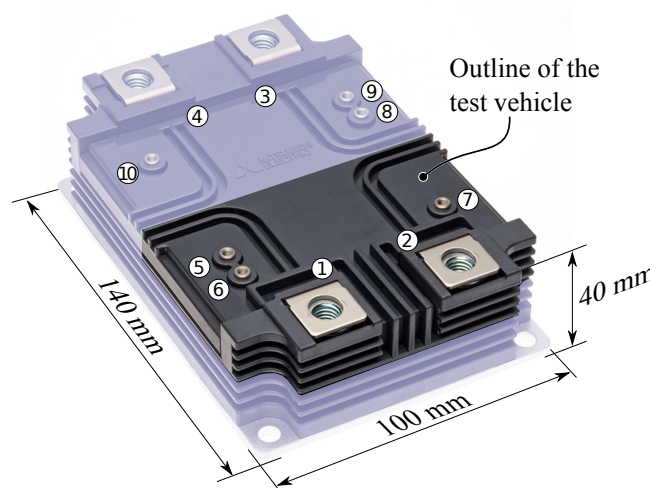


Fig. 1: Mitsubishi's IGBT Dual type X-series HV100 power module. The clear part of the picture represents the tested zone of this experimental study. The pins n°1 and n°2 are designed to fulfill the dielectric requirement from the IEC guidelines.

With this open standard module, the connector pattern and the footprint remain the same from one implementation to another, while manufacturers are free to design the internal layout or the external creepage features (Infineon, Wolfspeed, Hitachi with the XHP-3, XHV-7 and nHPD²-HV power modules respectively).

Because the location of the terminals is set with this open standard, there is little headroom for dramatic changes, e.g. to increase the creepage distances enough to operate at 10 kV or more. The material class also offers little possibility for improvements, as the materials used for power modules usually belong to material group I with a Comparative Tracking Index (CTI) ≥ 600 , the best class defined in the IEC standards. As a consequence, limiting the environmental pollution may be the only possibility to use a power package at a higher voltage than what it was designed for (packages are typically designed considering a pollution degree 2 according to the IEC standards). As a result, it can be interesting to extend the voltage rating of power modules, or, on the other hand, to limit the voltage de-rating due to harsh environment, by adding a protective element. In this paper, a focus is made on open standard power modules and more specifically their use ranging from pollution degree 1 (PD1) to pollution degree 3 (PD3).

2 Protective device concept

A protective device is designed to fit between the power module and the busbar connection (Fig. 2). The design is adjusted to the external surface of the power module for a perfect fit. Double lips are formed around the connections for a good sealing of the normally exposed conductive surfaces of the busbar. By doing so, the protection breaks the clearance and creepage lines between both DC terminals of the power module. In addition, the sealing can offer a strong resistance to creepage and provide a pollution-proof protection. As a result, the new shortest creepage path is now on the top surface of the busbar (between the heads of both connection screws in Fig. 2). To overcome this issue in our tests, the connection screws are encapsulated with some silicone sealant. Other solutions could be to use insulating screws or to add rims around any connections, using the remaining space without degradation of the switching performances. A similar approach can be found in [9] where the high voltage connections are isolated from each other with no creepage path in-between; in addition, some shielding of the terminals is achieved using field plates on the connection board to prevent field reinforcements.

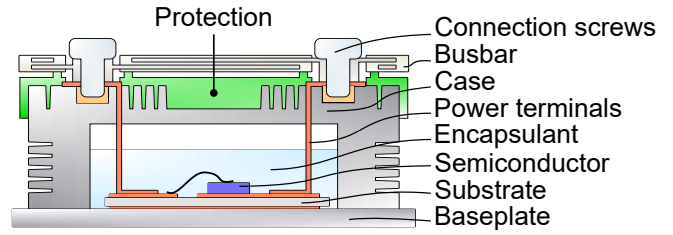


Fig. 2: the concept of the protection is to provide an easily mounting and removable part that fits between the power module and the busbar connections. The clamping force of the busbar helps to keep a good sealing of any connection usually in contact with air.

Tab. 1: Creepage distance (in mm) between the various terminals of the power module. In bold, the shortest distances with high differential electric stress.

Pin n ^o	2	3-4	BP	5-6	7	8-9	(10)
1	60	122	60	33	66	101	110
2	-	128	60	62	33	104	105
3-4	-	-	53	104	110	35	35
BP	-	-	-	70	70	70	70
5-6	-	-	-	-	70	105	90
7	-	-	-	-	-	85	128
8-9	-	-	-	-	-	-	75

3 Experimental setup

All the shortest creepage path lengths from any pair of terminals of an XHP-3 power module are reported in Tab. 1. Some short paths can be ignored since they are not undergoing high differential voltage (i.e.: pin n^o 1 and pin n^o 5 and 6 are source, source kelvin and gate terminals of the same switch, respectively). It appears that the minimum relevant creepage distance is observed between terminals n^o 3 and 4 (connected together inside the module) and the base-plate (BP). However, for handling and manufacturing reasons, this study focuses on the 60 mm creepage path between pin n^o 1 and pin n^o 2.

Maximum voltages applicable on this specific power module can then be determined with the creepage distance Tab. 2 derived from the IEC standard [6]. Considering the casing material is class I with a CTI ≥ 600 , the maximum allowed voltage for this specific casing design should not exceed 5 kV in PD3 conditions.

Tab. 2: Maximum rated rms voltage for a 60 mm creepage path between two terminals according to the material group of the considered insulation and the pollution degree [6].

	Mat I.	Mat. II	Mat III
PD1	12.5 kV	12.5 kV	12.5 kV
PD2	10 kV	7 kV	5 kV
PD3	5 kV	4 kV	4 kV

3.1 Test vehicles

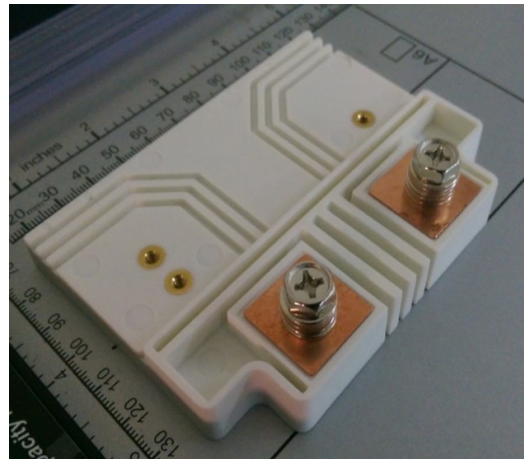
The protective device is made using injection molding of silicone rubber (Elastosil® LR3003, Wacker Chemie AG). The choice of this rubber is driven by its mechanical behavior (tear strength and hardness), as well as for the good contact quality and the insulation properties of silicone interfaces [10]. The protection device can be seen in Fig. 3(a).

Because the study focuses on the isolation between terminals 1 and 2, only a small part of the power module is needed (corresponding to the highlighted area in Fig. 1). Solid plastic parts (referred to as "dummy half-power modules" in the remaining of the article) are designed and fabricated. The half-power module is injection molded with a polybutylene terephthalate (PBT) plastic with 25% glass fiber for mechanical resistance. This choice of plastic (PBT ULTRADUR® B 4450 G5 from BASF) is also driven by fire resistance but above all for electrical properties such as resistivity and high CTI. Brass inserts with nickel finish are used to mimic the terminals of an actual power module. This is important, as these terminals could provide short paths for tracking failure. The power module terminals sheet-metal pads are reproduced with copper plates fixed flush to the corresponding pads with the brass insert underneath. A sample without protection and connector is depicted on Fig. 3(b) where the sheet-metal power terminals and brass inserts for signal connection are visible.

Flat connectors are used to reproduce the mechanical and electrostatic behavior of a typical busbar connection. All the exposed mechanical parts are nickel-plated to avoid unwanted galvanic corrosion in the presence of electrolytes. Stacks of washers are used to act as spacers between the connector and the power terminals, with a total height shorter than that of the protective device by about 500 μm, resulting in the compression of the silicone part to ensure a good sealing .



(a)



(b)



(c)

Fig. 3: (a) Protective device made from silicone rubber; (b) Sample before mounting, with sheet-metal terminals and brass insert connections; (c) Test vehicles assembly with the protective device.

This assembly is mounted with a 3.5 N m torque, as specified in the power module data-sheets. The screw heads are encapsulated with a salt water resistant silicone putty (SI 5366, Loctite®) to minimize the risk of arcing on the top of the assembly.

A total of 120 samples is mounted: 60 samples have a protection device mounted between the connectors and the module, while the 60 others have no protection. A protected sample can be seen in Fig. 3(c).

3.2 Artificial pollution pre-conditioning

Pre-conditioning is performed on samples to simulate harsh environmental conditions. Indeed, the hydrophobic properties of polymeric insulators can be affected by pollution. The pollution degrees are simulated as follows:

- PD1: laboratory conditions, no particular pre-conditioning is performed, the power modules are air-blown to remove any dust before mounting. These samples are considered PD2 when sprayed with water.
- PD2: non-conductive dust is applied. This non-conductive dust can change the surface tension of the power module casing, allowing a thin continuous film of water to form if high humidity or condensation is present. The pollution layer is simulated using kaolin (white clay). A suspension of 40 g L⁻¹ according to IEC 60507 is sprayed on the mounted power module. The sample is then dried at 50 °C for 30 min. This cycle is repeated 5 times until a continuous layer of kaolin is formed on the power module. This method, inspired from the dry powder method presented in [11], ensures a pre-conditioning on both the silicone rubber and PBT. The hydrophilic effect of the pollution pre-conditioning is visible for wet testing.
- PD3: this case corresponds to a non-conductive pollution which can become conductive in the presence of humidity. A method to simulate seashore pollution is described in [12]. Here, the power modules are mounted and placed in a salt-mist chamber (Fig. 4) for a total of 168 h according to the IEC 60068-2-11 standard.

The pollution degree reached according to the artificial pre-conditioning of the samples is summarized



Fig. 4: A total of 40 samples are placed in a salt mist chamber for PD3 pre-conditioning. Half of the samples are protected while the other half are not.

Tab. 3: Pollution degree reached according to artificial pollution conditioning for each series of test samples. Samples series marked with a * are also tested for partial discharges.

		Clean	Kaolin	Salt
Dry	bare	1*	2	3*
	protected	1*	2	3
Wet	bare	2	2	3*
	protected	2	2	3*

in Tab. 3. 40 samples are exposed to each pre-conditioning type, 20 equipped with the protective device, 20 without. To simulate the wet conditions, deionised water is sprayed on the modules just before the electrical tests.

3.3 Breakdown voltage and partial discharge tests

To perform the breakdown voltage tests, an ac 50 Hz voltage waveform is applied on the sample connectors through a 230 V / 50 kV transformer (Fig. 5). A 22 Ω resistor limits the current in the primary coil of the high voltage transformer. An isolation transformer with a 1 to 1 ratio is used for safety reasons. The voltage is controlled manually with an auto-transformer, following a 1 kV s⁻¹ ramp as close as possible. Since there is no arc detection in this setup, the circuit is manually de-energized when a first flash-over breakdown is observed. Breakdown voltage tests are destructive but they must be performed first to define the voltage range at which partial discharge measurement

Tab. 4: Number of samples dedicated to the breakdown voltage and PDIV tests among the 20 initial samples per pre-conditioned set. For bare wet samples with salt conditioning, the same samples are reused after dry tests. Series marked with a "+" are the protected series. C, K and S stands for Clean, Kaolin and Salt respectively.

	Vbr dry	Vbr wet	PDIV dry	PDIV wet
C	5	5	10	-
C+	5	5	10	-
K	5	5	-	-
K+	5	5	-	-
S	5	5	7	(7)
S+	5	5	-	7

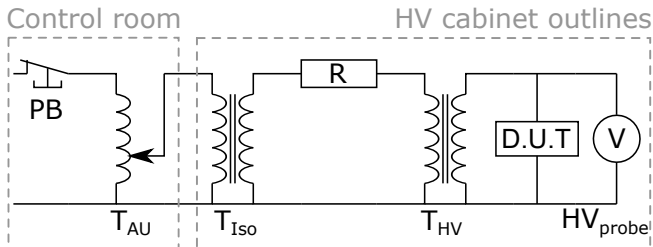


Fig. 5: Breakdown Voltage test setup.

can be performed safely. Each breakdown voltage measurement series consist of 5 samples for all pre-conditioning referenced in Tab. 3.

The partial discharge tests are performed in a high voltage cabinet with an ac 50 Hz voltage source of maximum 24 kV and a background noise of 0.2 pC. The detection system (Omicron) is connected in accordance with IEC 60270. The sample is placed in parallel of a coupling capacitor through which high frequency signals generated by partial discharges are measured according to IEC 60270 guidelines. To avoid introducing parasitic partial discharges and corona discharges at the sharp edges of a screw or crocodile clip connector, a custom part (an oblong piece of brass with a female banana socket) is used to connect the samples to the test setup.

To measure the partial discharge inception voltage (PDIV) a ramp of 1 kV s^{-1} is applied until the sustained partial discharges are generated; the voltage is then reduced to 0 and this cycle is repeated at least 5 times (Fig. 6). The PDIV threshold is 10 pC as it is a standard value for electronic devices. A set of 7 to 10 samples are used for each partial discharge test series as mentioned in Tab. 4. Partial

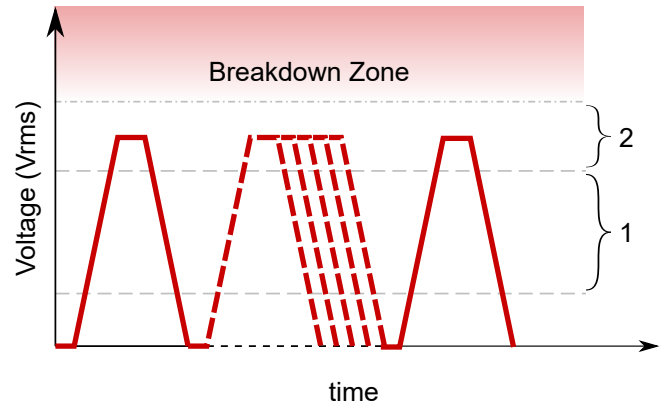


Fig. 6: Partial discharge test procedure consist of repeated voltage application on the test sample. The PDIV is measured in the voltage zone 1, the partial discharge regime is observed in the voltage zone 2.

discharge tests are considered non-destructive, so to minimize the use of samples, the bare PD3 dry samples are reused for bare PD3 wet samples.

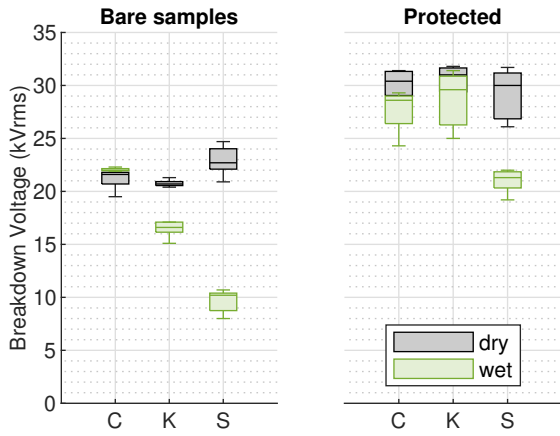
4 Test Results and Discussion

4.1 Breakdown voltage tests results

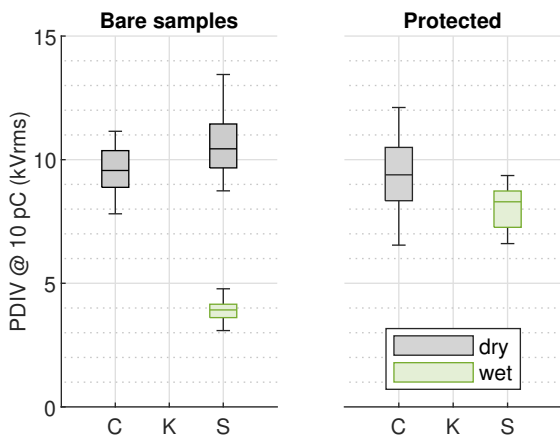
The results of breakdown voltage tests are shown in Fig. 7(a). Protected samples have a higher breakdown voltage than non protected samples. For non protected samples, artificial pollution lowers the breakdown voltage when activated with humidity. The breakdown voltage for protected samples in PD1 and PD3 are within the same statistical range. The effect of humidity is no longer visible except for salt polluted samples. However, the breakdown mechanism differ from bare samples: the flash-over takes place along the connectors (busbars) for protected samples (Fig. 8(a)), while on the bare samples, it occurs between the power terminals of the module (Fig. 8(b)). This means that with the protection in place, the breakdown voltage of the module and its terminals exceeds that of the busbars.

4.2 Partial discharge tests results

Following the test procedure, a minimum of 5 PDIV measurement per sample is recorded. The mean value for each sample is calculated. Figure 7(b) represents a boxplot of average values for each sample sorted by type of series. A first result is the degradation of the PDIV for non-protected wet samples with a salt pollution, which could be expected

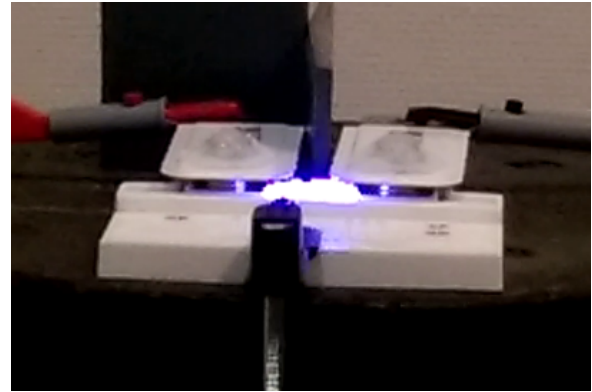


(a)



(b)

Fig. 7: (a) Boxplot of the breakdown voltage tests results versus the conditioned type samples; (b) Boxplot of the Partial Discharge Inception Voltage tests results versus the conditioned type samples.



(a)



(b)

Fig. 8: (a) flash-over on a bare sample, the arc is formed between the two terminals; (b) flash-over on a protected sample, the arc is formed on the top of the connections. An insulating barrier is placed between the connectors to manage the clearance distance between exposed metal at the end of the connectors.

for actual power modules. When the samples are protected, even salt-conditioned and wet samples have a PDIV comparable to that of dry PD1 protected samples. This result demonstrates the effect of pollution on PDIV values of devices, but it also demonstrates the efficiency of the protection.

5 Conclusion

A protection has been designed to address the voltage de-rating of power modules under harsh environment up to PD3. At first, breakdown voltages are performed to test the capability of such a device to withstand electrical stress. It shows + 47 % increase of breakdown voltage for PD1 samples and + 120 % for wet PD3 samples over non-protected samples. The protection is found to be efficient to prevent arcing since no breakdown is observed any more at the protection – module interface.

Partial discharge tests are also performed to ensure that the protection does not degrade the dielectric performance of the interconnects. The PDIV levels of protected samples remain similar to those of un-protected clean samples, while un-protected samples exhibit a strong drop in PDIV for wet PD3 conditions. Here again, the protection is found to be efficient to maintain PDIV constant despite harsh environmental conditions.

The dielectric characterizations validate the concept of the protection for high voltage power modules, allowing to use compact power module outlines for higher voltages. On the other hand, the protection can be a solution to avoid the voltage de-rating when the power module is used under harsh environment. The breakdown voltages on protected samples highlighted a new weakness point on the power module and busbar assembly as shown in Fig. 8. However, this weak point could easily be managed with a proper busbar design considering standard creepage, clearance, coating or potting solution.

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