A 6.5kV IGBT Module with very high Safe Operating Area

A. Kopta, M. Rahimo, U. Schlapbach, D. Schneider, Eric Carroll, S. Linder

IAS, October 2005, Hong Kong, China

A 6.5kV IGBT Module with very high Safe Operating Area

A. Kopta, M. Rahimo, U. Schlapbach, D. Schneider, Eric Carroll, S. Linder
ABB Switzerland Ltd, Semiconductors
Lenzburg, Switzerland
arnost.kopta@ch.abb.com

Abstract — **A new 6.5kV IGBT module is presented. This module, using High Voltage Soft-Punch-Through technology exhibits an exceptionally high Reverse Bias Safe Operating Area and withstands dynamic avalanche up to its rated voltage. This capability allows the module to be operated with a gate resistance 10 times lower than present generations of 6.5 kV modules of the same nominal rating, allowing fast turn-off and hence reduced turn-off losses. The chip technology will be briefly described and detailed test results highlighting the smooth switching characteristics, extremely safe operating areas and high tolerance to stray inductance will be presented. The importance of fast switching through low values of gate resistance will be explained in terms of loss-reduction, gate-drive simplification and good dynamic current sharing between chips within the module.**

Keywords—IGBT, power module, safe operating area

I. Introduction

One of the main challenges in the development of 6.5kV IGBTs and diodes has always been to obtain a sufficiently large safe operating area (SOA) as required by many power electronic systems operating under hard-switching conditions. Under these high stress conditions, previous device generations suffered from ruggedness limitations caused by shortcomings in the device designs. To overcome the insufficient IGBT and diode ruggedness, device manufacturers and system designers in the past resigned themselves to a number of operational limits such as de-rating and the use of voltage clamps, snubbers and high gate resistances, to achieve the necessary switching capability. Last year ABB announced a breakthrough in SOA performance for high voltage IGBTs and diodes employing the planar Soft Punch Through (SPT) design platform. This new technology enables the devices to withstand the critical, formerly unsustainable, phase of dynamic avalanche resulting in a remarkable increase of ruggedness. Based on this design platform, ABB now introduces a newly developed 6.5kV chip-set, confirming the excellent switching SOA of this technology.

Packaged in the new HV-HiPak™ module (Fig. 1), the 6.5kV chips offer the ease-of-use long awaited by designers of high power, high voltage converters. The high dynamic ruggedness, combined with the SPT technology smooth switching behaviour gives users the greatest freedom in designing their systems without the need for any dv/dt or peak-voltage limiters such as snubbers or clamps. The extended SOA furthermore allows higher switching speeds, which in turn translate into lower switching losses. As will be demonstrated in this article, the 6.5kV HV-HiPak™ module simply sets new standards in terms of robustness and overall electrical performance for high reliability applications.

Figure 1. The new 6.5kV/600A HV-HiPak™ module with SPT-IGBT and diode technology.

II. The 6.5kV HV-HiPak™ Module

The 6.5kV HV-HiPak™ module is an industry-standard housing with the popular 190 x 140 mm footprint. It uses Aluminium Silicon Carbide (AlSiC) base-plate material for excellent thermal cycling capability as required in traction applications and Aluminium Nitride (AlN) isolation for low thermal resistance. The HV-HiPak™ version utilized for the 6.5kV voltage class is designed with an isolation capability of $10.2kV_{RMS}$.

To achieve the high reliability required by its targeted applications (e.g. traction), the HV-HiPak™ module has been optimised for operation in harsh environments. This has been accomplished by designing the 6.5kV SPT chips to have smooth switching characteristics and rugged performance, qualities that are essential in the high-inductance environments of high voltage power electronic systems. The internal wiring and layout of the module were optimised in order to minimise oscillations and current imbalances between the chips. Finally, the whole design was qualified by standard reliability tests including HTRB (High Temperature Reverse Bias), HTGB (High Temperature Gate Bias), THB (Temperature Humidity Bias 85°C/85% relative humidity), APC (Active Power Cycling) and TC (Temperature Cycling).

III. 6.5kV Chip-Set Technology

The newly developed 6.5kV chip-set was designed to reach high levels of dynamic SOA capability, combined with a carefully selected trade-off between losses, high immunity against cosmic ray induced failures and smooth switching behaviour. The new HV-IGBT design platform uses an advanced and extremely rugged planar cell, which was primarily developed in order to significantly increase the cell latch-up immunity during dynamic avalanche in order to achieve large SOA. The use of the Soft-Punch-Through (SPT) buffer concept allows a substantial reduction of the n-base region thickness without compromising any other electrical parameters. One of the main features of the SPT buffer is that it allows the current curve to smoothly decrease during the turn-off transient, hence, the term "Soft" in SPT. Thanks to the combination of cell design and thin wafer, the new 6.5kV IGBT has low overall electrical losses. The SPT-buffer, in combination with the anode design, further ensures good short circuit controllability with a high Short Circuit Safe Operating Area (SCSOA). In the design of today's high voltage IGBTs and diodes, the trade-off between cosmic ray withstand capability and switching characteristics has become critical. Cosmic ray ruggedness can be improved by increasing silicon thickness, resistivity or by a combination of both. Increasing the silicon thickness inevitably leads to higher losses, whereas a high resistivity degrades switching behaviour and controllability of the chip. The starting material of the 6.5kV chip-set was designed to reach a cosmic ray induced failure rate of 100 FIT/HiPak™ module at a DC rail voltage of 3800V, while the SPT buffer and anode design was optimised for turn-off waveform smoothness.

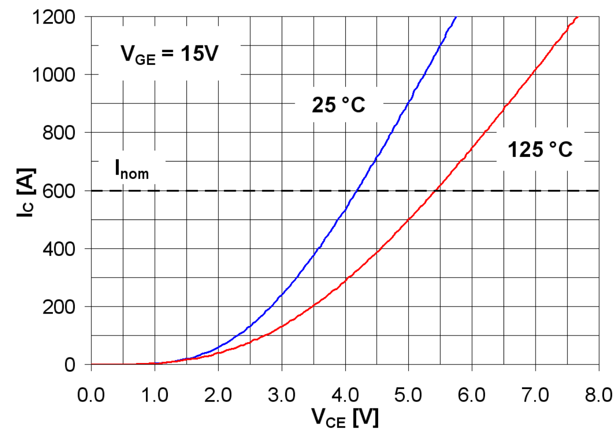
To complement the advantages of the 6.5kV SPT-IGBT, a new 6.5kV fast/soft recovery SPT-diode was developed. The main advantage of this new diode is its large SOA combined with very low on-state and reverse recovery losses. The design uses a highly doped p^+ anode, which gives the diode its rugged reverse recovery performance. A highly doped p^+ anode eliminates problems such as inhomogeneous current distribution and "reach-through" effects during dynamic avalanche, normally associated with low-doped p-anode designs. The high p^+ doping also facilitates the creation of a robust junction termination to eliminate high fields and current crowding at the anode periphery during reverse recovery, which would jeopardise ruggedness. The electrical parameters of the diode were adjusted using a novel dual local lifetime control method. This method allows an optimal shaping of the electron-hole plasma for tailoring the electrical parameters and further enhancing SOA. In this way, the new diode design achieves the best trade-off to-date between forward voltage drop and turn-off losses. Furthermore, the dual lifetime control method also assures a strong positive on-state voltage temperature coefficient, required for good current distribution between the individual diodes in the module.

IV. 6.5kV/600A HV-HiPak™ Electrical Performance

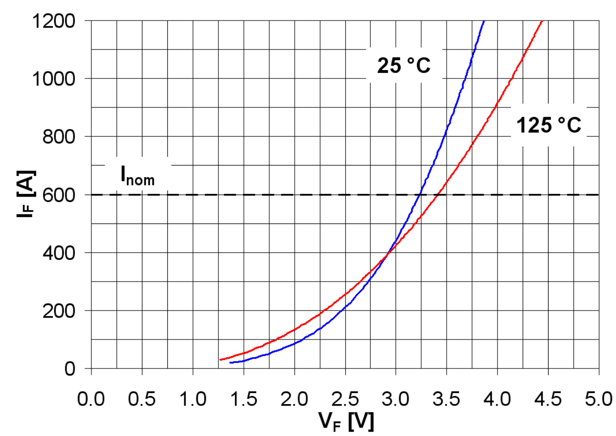
The described module has been designed with the objective of eliminating the heretofore-inherent weaknesses of HV IGBTs, which were particularly apparent at 6.5 kV. This has been achieved by endowing the present devices with the dynamic avalanche capability seen only in lower voltage IGBTs. HV-SPT technology has been extended to this voltage class to ensure smooth, controlled switching under all adverse conditions most notably those of the inevitably high stray inductances found in HV systems.

A. 6.5kV/600A HV-HiPak™ Characteristics under Nominal Conditions

To demonstrate the excellent electrical performance of the new 6.5kV HV-HiPak™ module, extensive testing of both the static and dynamic characteristics was carried out. Fig. 2a and 2b show the on-state curves of the 6.5kV SPT-IGBT and diode at room temperature and at 125 °C respectively. At a nominal current of 600A, the IGBT has a typical on-state voltage drop of 4.2V at 25 °C and 5.4V at 125 °C. The on-state curve exhibits a strong positive temperature coefficient even at very low current levels, which ensures good current sharing in the module. The diode has a very low forward voltage drop of 3.2V at 25 °C and 3.4V at 125 °C at 600A, showing a positive temperature coefficient already well below the nominal current.



(a) Forward characteristics of the 6.5kV SPT-IGBT



(b) Forward characteristics of the 6.5kV SPT-diode

Figure 2. 6.5kV/600A HV-HiPak™ forward I-V characteristics for the SPT-IGBT (a) and SPT-diode (b).

Fig. 3 shows the turn-off waveforms of the 6500V/600A HiPak™ under nominal conditions, i.e. a DC rail voltage of 3600V and a current of 600A, at a temperature of 125 °C. The test was conducted using a circuit stray inductance (L_σ) of 300nH. In spite of this high stray inductance, the current and voltage waveforms of the SPT-IGBT are both still very smooth, showing no abrupt changes or oscillations. This excellent switching behaviour was achieved by a careful optimisation of the SPT buffer layer. The anode was designed to have a low emitter efficiency, which results in a short turn-off current tail and low turn-off losses, since less charge has to be extracted during the turn-off transient. In this way, a perfect balance between low losses, short tail current and low EMI levels is achieved. Thanks to the optimised planar cell design and the thin-wafer SPT-concept, the 6.5kV IGBT reaches a very competitive point on the $V_{CE,on}$ / E_{off} technology curve with typical turn-off losses of 3.25J at nominal conditions.

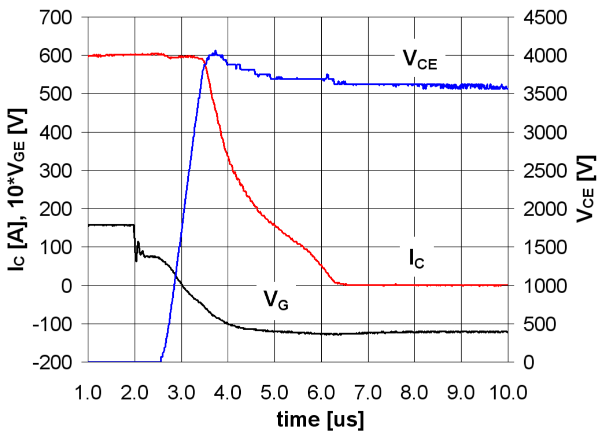


Figure 3. 6500V/600A HV-HiPak™ IGBT nominal turn-off waveforms. V_{CC} = 3600V, I_C = 600A, R_{Goff} = 2.7Ω, L_σ = 300nH, T_j = 125 °C.

In Fig. 4 and 5, the module turn-on and reverse recovery characteristics under nominal conditions can be seen respectively. The combination of the new low-loss SPT-diode and an optimised IGBT input capacitance brings the turn-on switching losses down to a typical value of 4.25J. The turn-off, turn-on and reverse recovery energy losses of the module are plotted as a function of the collector current are shown in Fig. 6 and Fig. 7 respectively. The turn-off, turn-on and reverse recovery energy losses of the module are plotted as a function of the collector current and gate resistance in Fig. 6 and Fig. 7. Thanks to the new dual local lifetime control method, the diode achieves the best trade-off between static and dynamic losses in this voltage class, with a reverse recovery charge (Q_{rr}) of 1.15mC and reverse recovery losses (E_{rec}) of 2.10J at nominal conditions.

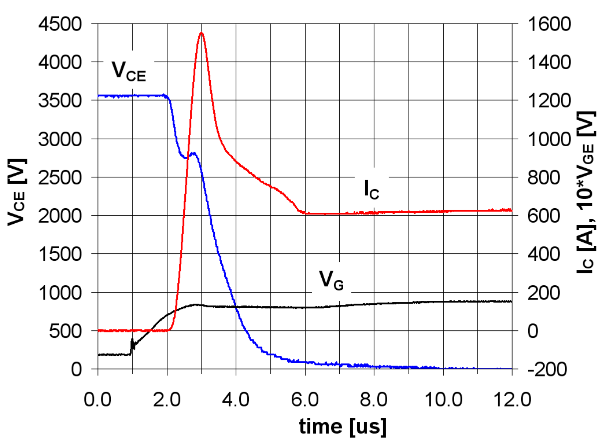


Figure 4. 6500V/600A HV-HiPak™ IGBT turn-on waveforms at nominal condition. V_{CC} = 3600V, I_C = 600A, R_{Gon} = 3.9Ω, L_σ = 300nH, T_j = 125 °C.

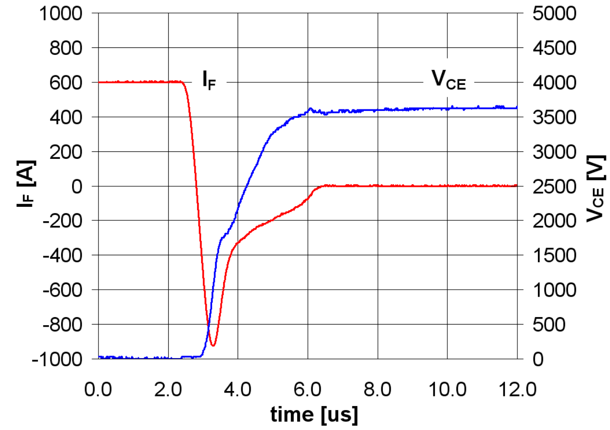


Figure 5. 6500V/600A HV-HiPak™ diode reverse recovery characteristics nominal condition. V_{CC} = 3600V, I_C = 600A, R_{Gon} = 3.9Ω, L_σ = 300nH, T_j = 125 °C.

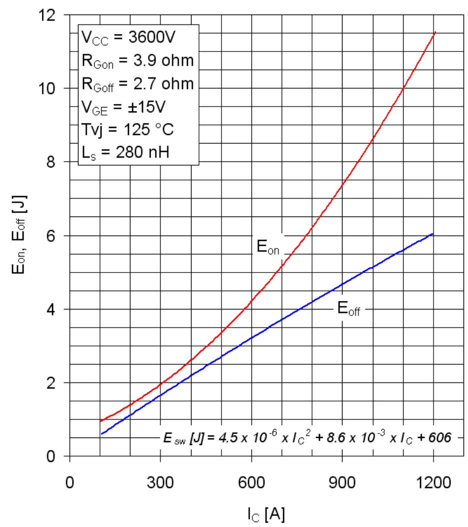


Figure 6. 6.5kV/600A HV-HiPak™ E_{on} and E_{off} vs. I_c losses curves.

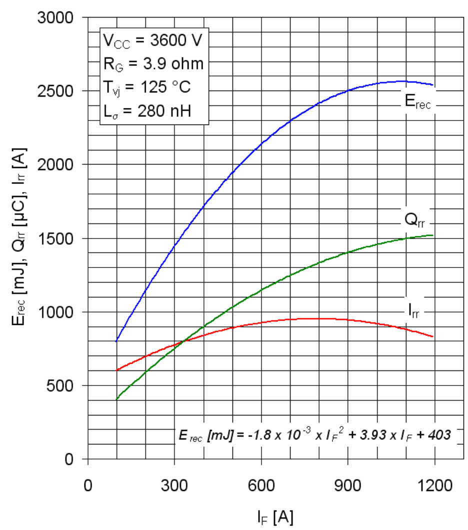


Figure 7. 6.5kV/600A HV-HiPak™ E_{rec}, I_{rr}, Q_{rr} vs. I_F losses curves.

For reference, the turn-off, turn-on and reverse recovery energy losses of the module are also plotted as a function of the gate resistance and commutation di/dt in Fig. 8 and Fig. 9.

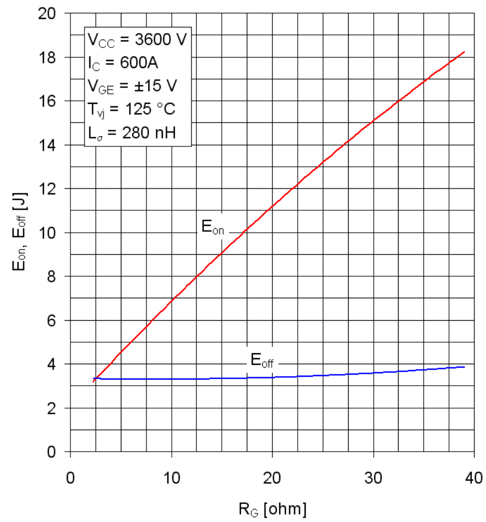


Figure 8. 6.5kV/600A HV-HiPak™ E_{on} and E_{off} vs. R_g curves.

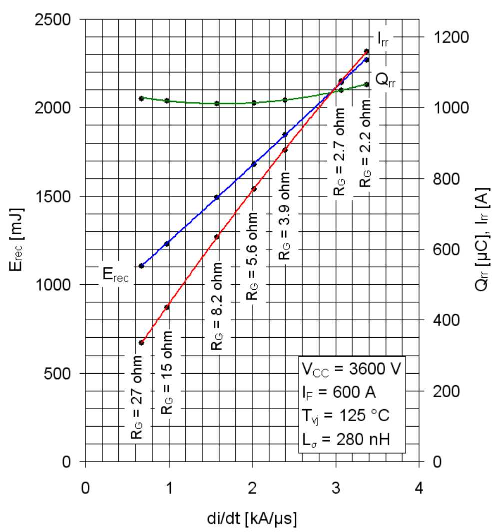


Figure 9. 6.5kV/600A HV-HiPak™ E_{rec}, I_{rr}, Q_{rr} vs. di/dt curves.

B. *6.5kV/600A HV-HiPak™ Ruggedness*

One of the biggest advantages of the new 6.5kV SPT-IGBT is its unmatched turn-off ruggedness. In Fig. 10, the waveforms of an RBSOA test, in which the module was switched under extreme conditions, can be seen. The device was tested at 125 °C with a current of 1500A (corresponding to 2.5 times the rated current) and a DC rail voltage of 4400V. In addition, a large stray inductance of 300nH was used and a low gate resistance of only 1.5 ohms. No active clamps or snubbers were used in the test. Another major advantage of an extremely rugged IGBT is that it offers the possibility of operating the device with significantly lower gate resistance values (R_{Goff}) than those required by conventional technologies. This results in shorter delay times during device turn-off, which not only lowers the turn-off losses but also improves the current sharing between individual IGBT chips in the module. The new 6.5kV/600A HV-HiPak™ module takes full advantage of this feature and is the first 6.5kV module ever to reach operational modes previously attained only by devices of lower voltage classes. A further advantage is that no dv/dt nor peak voltage restrictions apply to these devices such that snubbers and clamps are not required for high turn-off capability.

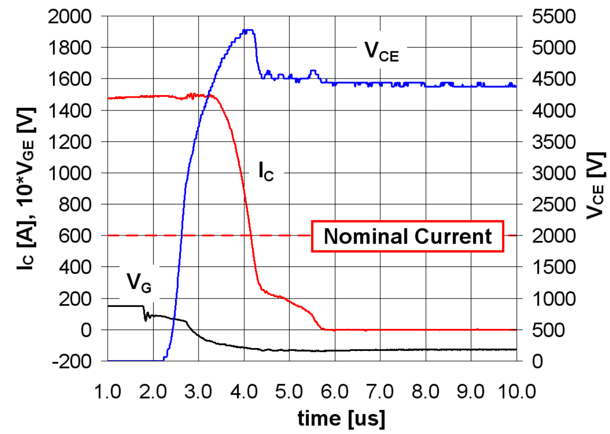


Figure 10. 6500V/600A HV-HiPak™ IGBT turn-off characteristics under high SOA conditions. V_{CC} = 4400V, I_C = 1500A, R_{Goff} = 1.5Ω, L_σ = 300nH, T_j = 125 °C.

Fig. 11 shows the 6500V/600A HV-HiPak™ diode reverse recovery under SOA conditions with a high DC rail voltage, a large stray inductance and a low gate resistance (R_{Gon}) in order to achieve a high commutation di/dt.

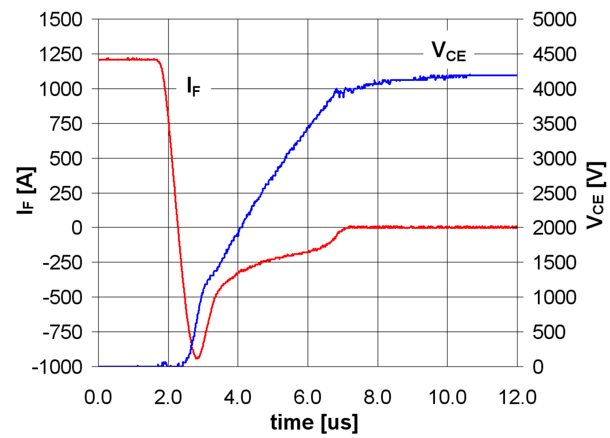


Figure 11. 6500V/600A HV-HiPak™ diode reverse recovery characteristics under SOA stress. V_{CC} = 4400V, I_F = 1200A, R_{Gon} = 3.9Ω, L_σ = 300nH, T_j = 125 °C

Thanks to its large SOA capability, the new 6.5kV SPT-diode can be switched significantly faster than conventional 6.5 kV diodes. As a result, the turn-on losses of the IGBT can be significantly lowered. The dynamic diode behaviour exhibits soft recovery and rugged performance under all operating conditions including adverse combinations of low current, high DC voltage and low temperature.

C. *6.5kV/600A HV-HiPak™ Short Circuit Performance*

Finally, Fig. 12 and 13 show the 6.5kV HV-HiPak™ during a short circuit pulse of 10μs with a subsequent soft turn-off at 25 °C and 125 °C respectively. The test was conducted at a DC rail voltage of 4500V.

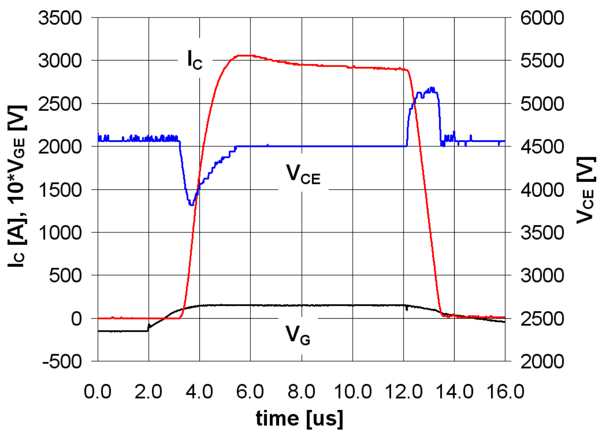


Figure 12. 6500V/600A HV-HiPak™ SCSOA characteristics.
V_{CC} = 4500V, R_{Goff} = 3.9Ω, V_{GE} = 15V, L_σ = 300nH, T_j = 25 °C

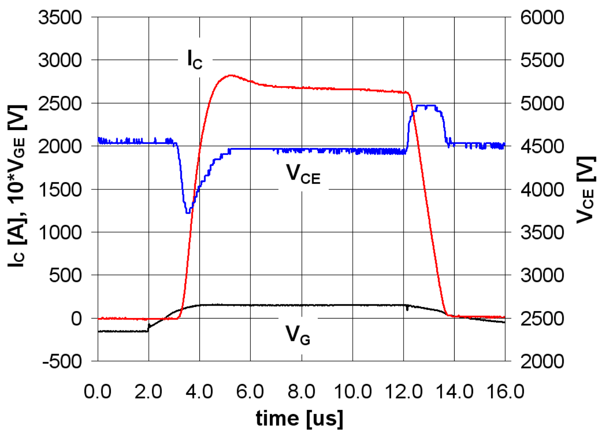


Figure 13. 6500V/600A HV-HiPak™ SCSOA characteristics.
V_{CC} = 4500V, R_{Goff} = 3.9Ω, V_{GE} = 15V, L_σ = 300nH, T_j = 125 °C

The SPT buffer and anode designs employed in the 6.5kV IGBT have been optimised in order to obtain a high short circuit SOA capability, even withstanding the short circuit conditions at gate voltages exceeding the standard drive voltage of 15V. This is important for the following two reasons: Firstly, if a short circuit occurs during IGBT conduction, the effective gate-emitter voltage (V_{GE}) can increase significantly as a result of gate-voltage "pumping" caused by the charging of the gate-collector capacitance during the collector-emitter (V_{CE}) voltage rise. Secondly, at lower temperatures, the short circuit current level will increase due to a reduction in the MOS-channel resistance. Since the short-circuit capability strongly depends on the short circuit current level, low temperatures will be more critical for the IGBT in this mode. As the temperature decreases, the short-circuit failures will consequently occur at decreasing gate voltages. Hence, to be able to withstand a 10 µs short-circuit pulse with a gate voltage of 15V at –40 °C, the 6.5kV SPT-IGBT was designed to have a room temperature short circuit capability with V_{GE} above 17V.

V. Conclusions

In this article, we presented our newly developed 6.5kV HV-HiPak module. The main feature that characterises the new product from state-of-the-art is the record-breaking SOA (Safe Operating Area). The new high voltage SPT-IGBT and diode technology has established new standards in ruggedness. Now, the latest expansion of this design platform to 6.5kV confirms this planar technology's unparalleled robustness. The new HV-HiPak™ module exhibits excellent overall electrical characteristics and are capable of withstanding extreme conditions during turn-off and short circuit operation. The resulting module, by simplifying gate-drive and protection requirements, will greatly contribute to the reliability and cost-effectiveness of HV converters.

References

[1] M. Rahimo et al., "2.5kV-6.5kV Industry Standard IGBT Modules Setting a New Benchmark in SOA Capability" Proc. PCIM'2004, NURNBERG, GERMANY, 2004, pp 314-319. M. Rahimo et al., "Switching-Self-Clamping-Mode "SSCM",

[2] a breakthrough in SOA performance for high voltage IGBTs and Diodes" Proc. ISPSD'2004, JAPAN, May 2004, pp 437-440.