The Next Generation 6500V BIGT HiPak Modules

Liutauras Storasta, Arnost Kopta, Munaf Rahimo, Charalampos Papadopoulos, Silvan Geissmann, Raffael Schnell
ABB Switzerland Ltd, Semiconductors, Fabrikstrasse 3, CH - 5600 Lenzburg, Switzerland,
Tel: +41 58 586 18 24, email: liutauras.storasta@ch.abb.com

The Power Point Presentation will be available after the conference

Abstract

In this paper we present the latest developments at ABB utilizing the Bi-mode Insulated Gate Transistor (BIGT) chip. The adaptation of the BIGT technology in the 6500V HiPak module range enables the highest output power per footprint for this voltage class to be achieved. Detailed electrical characterization of the newly developed 600A modules is provided highlighting the key performance improvements brought in by the new technology: increased output current, smooth switching waveforms and uncompromised diode surge capability. Device capabilities under extreme operating conditions are demonstrated and compared to those of the state-of the art SPT IGBT modules. Furthermore, application related issues are addressed focusing on the gate drive control in the diode mode of operation.

1. Introduction

The use of reverse conducting devices in the high power IGBT modules offers clear advantage of eliminating the antiparallel diodes and offering a possibility to increase the power per footprint of the module [1] [2]. However, design of a high power hard-switched reverse conducting IGBT (RC-IGBT) meeting the performance requirements implied on semiconductors by the industry is a challenging task. ABB has developed a new high performance reverse conducting IGBT to be used in high power applications, which is referred to as the Bi-mode Insulated Gate Transistor (BIGT) [3]. Basic feasibility studies of the concept from early prototypes were presented in 2009, and in 2010 HiPak power modules with 3300V ratings have been demonstrated along with the detailed static and switching performance data [4] [5] [6]. The BIGT has been shown to bring a lot of advantages compared to the standard two-chip IGBT/diode approach.

Continuous optimization of the BIGT design is on-going to further improve the new concept of the chip and to scale it up towards higher voltages. This effort resulted in the 6500V HiPak1 module, presented in this paper. The new BIGT chips are characterized by lower losses due to a second generation enhancement cell design and optimized active to termination area ratio through improved chip scaling, extremely smooth switching waveforms without oscillations under extreme conditions and high diode surge current for a given module size.

2. The 6500V BIGT module

2.1. The BIGT Concept

The BIGT is an advanced reverse conducting IGBT device concept which mainly targets replacing high voltage IGBTs and diodes in the next generation systems [7]. The BIGT is a two-step integrated structure: In the first step, the diode is integrated in the IGBT creating the reverse-conducting RC-IGBT. The RC-IGBT cannot be used in high power applications requiring extensive paralleling of the chips due to the snap-back behavior at low temperatures in the transistor on-state mode. This is solved by the second step of integration, where the RC-IGBT is combined with an IGBT into a single hybrid chip as illustrated in Fig. 1. This ensures that hole injection occurs at low voltages and currents from the P+ pilot-anode in the IGBT

section of the BIGT. To further improve the on-state losses, the radial design of the anode shorts is employed [8].
As a result the device can operate in both freewheeling diode mode and (IGBT) transistor mode by utilizing essentially the same available silicon volume in both modes. As all the chips in the module are able to operate in both modes, available silicon area can be increased by approximately 50% for the IGBTs and 200% for the diodes, compared to the standard HiPak module (IGBT:diode ratio 2:1). The thermal resistance between the junction and the case is also reduced accordingly. Furthermore, by using this approach the same silicon volume is heated during IGBT and diode operation modes and the temperature ripple is significantly reduced, delivering increased reliability of the module.

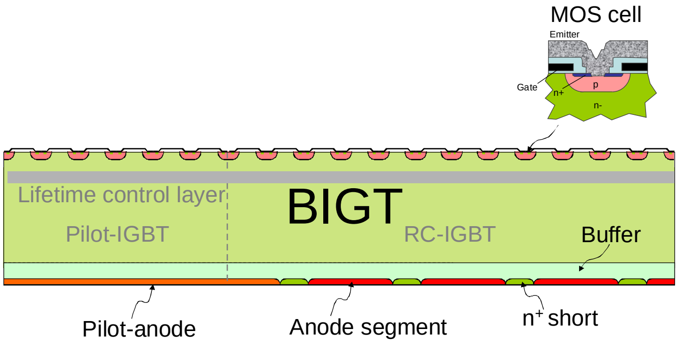

Fig. 1. The BIGT device structure

To achieve good BIGT diode mode switching performance, several measures have to be applied: optimization of the doping profiles of the p-well of the MOS cells for low injection efficiency, carrier lifetime control in the p-well, and additionally a uniform carrier lifetime adjustment in the n-base. The latter process has an influence on the increased conduction losses in both IGBT and diode modes, which limits the output current capability of the chip at low frequencies.

Fig. 2. High voltage HiPak 1 BIGT module rated at 6500V and 600A

2.2. The BIGT HiPak module

6500V BIGT HiPak1 (140 x 130) mm modules (see Fig. 2) were fabricated using the standard high voltage HiPak process, with every chip position (diode or IGBT) replaced by a 25A BIGT chip. This resulted in a 600A module with 24 chips working in parallel, as opposed to 16 IGBT and 8 diodes normally found in such modules. The modules were tested under the same conditions applied to state-of-the-art 600A rated IGBT modules, currently available in HiPak2 size (140 x 190) mm.

The same BIGT chips could be also assembled into a HiPak2 module, providing space for 36 BIGT chips, thus producing a 900A module. Such output currents in a 6500V module today can only be realized by using BIGT technology.

3. Electrical performance

3.1. Static characteristics

The on-state characteristics in the IGBT and the diode modes for the 6500V HiPak1 module are shown in Figure 3 at 25ºC and 125ºC. The module exhibits low static losses together with strong positive temperature coefficient for safe paralleling of chips. The radial layout of the anode shorts ensures that the on-state curves of the IGBT mode are completely smooth and without signs of a snap-back. During the diode conduction, the gate voltage has a strong influence on the conduction losses, as it controls the plasma shape near the emitter contact. With the gate voltage positive, the MOS channel is formed and the p-well is partially shorted to the emitter contact, causing a lower injection from the p-well. When the gate voltage drops below the threshold, the MOS channel is removed and the built in diode exhibits the lowest conduction losses. This results in two distinctly different on-state characteristics of the diode at V_{GE}=0V (or -15V) and V_{GE}=15V. At nominal current (600A) and T_j=125°C, the BIGT HiPak has a typical on-state voltage drop of 4.35V in IGBT mode. In the diode mode with the gate voltage 0V or below, the on-state voltage drop is 4.0V. With the gate voltage positive, diode losses rise to 6.0V, which has to be avoided through smart gate control. A more detailed treatment of the MOS control during switching is given in the last section of the paper.

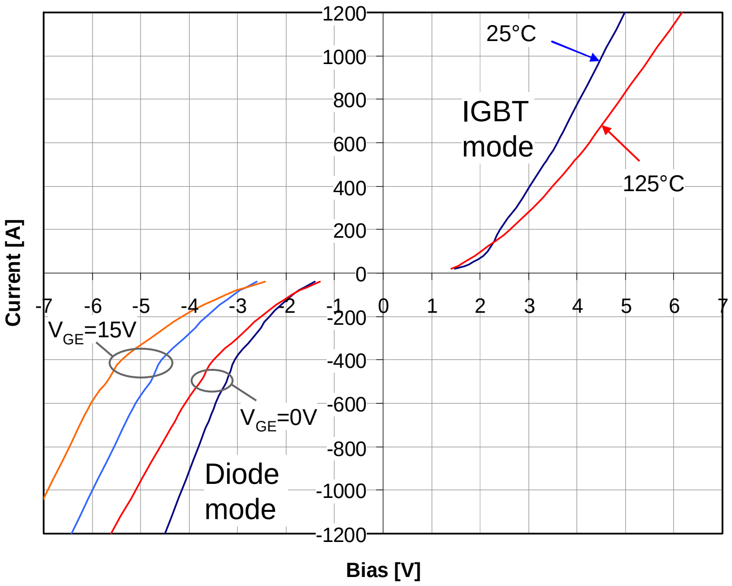

Fig. 3. Forward characteristics of the 6.5kV/600A BIGT HiPak1 in IGBT and diode modes

3.2. Nominal switching characteristics

In Figures 4, 5 and 6 the module-level waveforms are shown and compared between 600A SPT IGBT/diode Hipak2 and BIGT HiPak1 under nominal switching conditions (V_{DC}=3600 V, I_C=600 A, T_j=125°C). The respective module switching losses are also indicated. The BIGT shows slightly higher turn-off losses due to different optimization of the anode. The waveforms demonstrate the normal BIGT switching behavior in both IGBT and diode modes when compared to a state-of-the-art device. Some dynamic avalanche is visible in the BIGT module, but is nevertheless in the same range as for the IGBT/diode modules optimized for the same technology curve point. The waveforms of the BIGT module are much smoother than that for a standard module in both IGBT and diode modes and under no conditions the BIGT shows oscillations or voltage overshoots due to current tail snap-off [3].

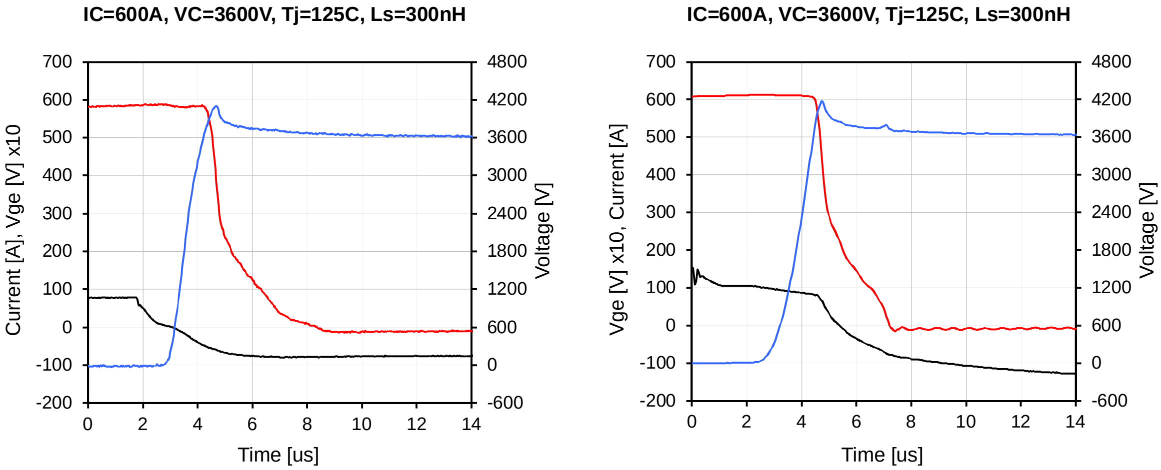

Fig. 4. 6.5kV/600A BIGT HiPak1 (left) and 6.5kV/600A IGBT/diode HiPak2 (right) IGBT-mode turn-off waveforms under nominal conditions

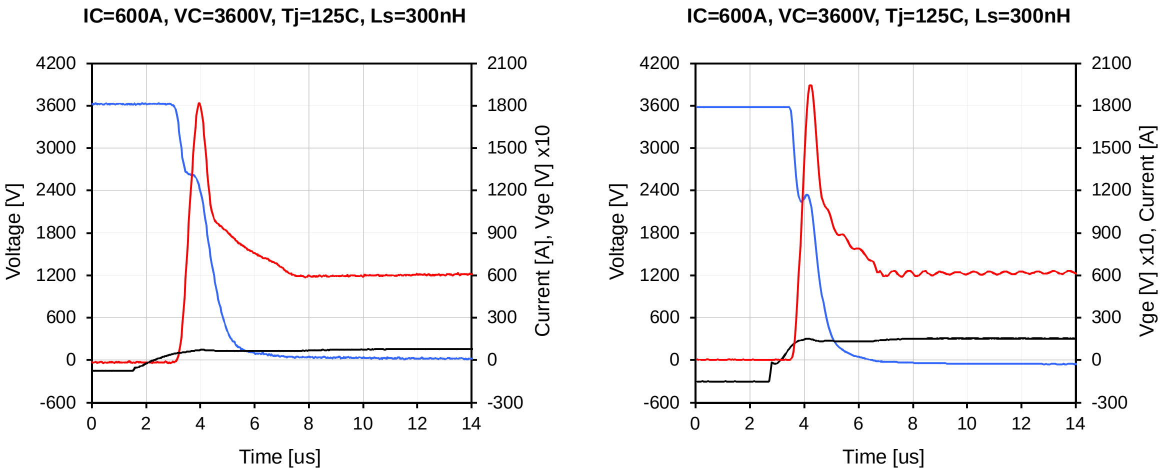

Fig. 5. 6.5kV/600A BIGT HiPak1 (left) and 6.5kV/600A IGBT/diode HiPak2 (right) IGBT-mode turn-on waveforms under nominal conditions

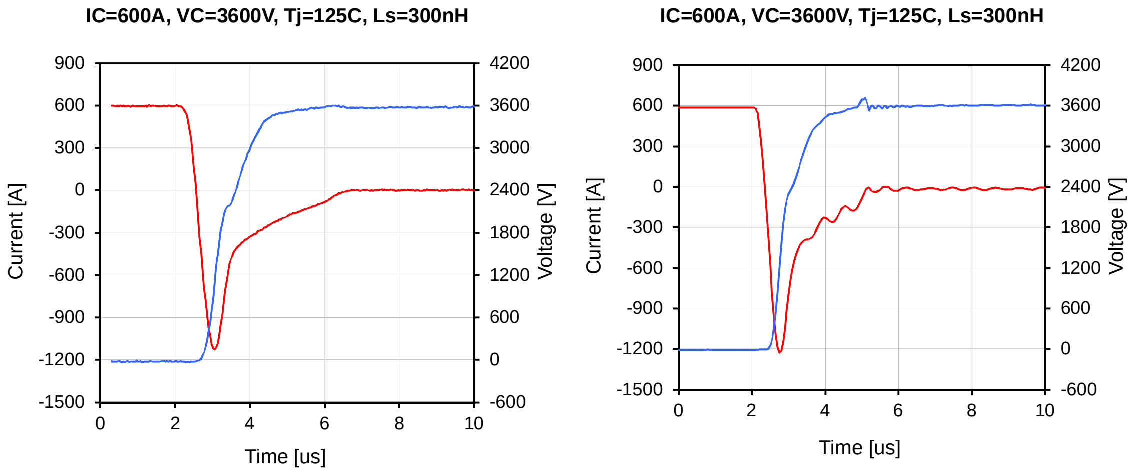

Fig. 6. 6.5kV/600A BIGT HiPak1 (left) and 6.5kV/600A IGBT/diode HiPak2 (right) Diode-mode turn-off waveforms under nominal conditions

3.3. SOA and Softness performance

The turn-of SOA of the BIGTs chips is not compromised and is equivalent to that of the corresponding IGBT chip. The HiPak module performance under a standard production SOA test is shown in Fig. 7 for turning off twice the nominal current of 1200A against a DC link voltage of 4500V and Tj=125°C.

The BIGT has inherently extremely soft switching behavior in both IGBT and diode modes of operation [7], as already evident from the nominal switching waveforms. During the turn-off tail in both modes, the passing electrons towards the n+ shorts (see Fig. 1) will forward bias the anode’s PN junction resulting in hole injection into the base and providing the necessary charge for smooth current decay. This feature is of particular importance for the realization of the BIGT technology since it overcomes the expected trend of reduced softness due to the non-optimum silicon design of the BIGT for diode mode operation and the increased diode area provided. The reverse recovery softness performance of the BIGT is demonstrated in Fig. 7 at ½ of the nominal current (300A) and V_{DC}=4500V and T_j=125°C, which typically yield the high overshoot voltages in conventional diodes.

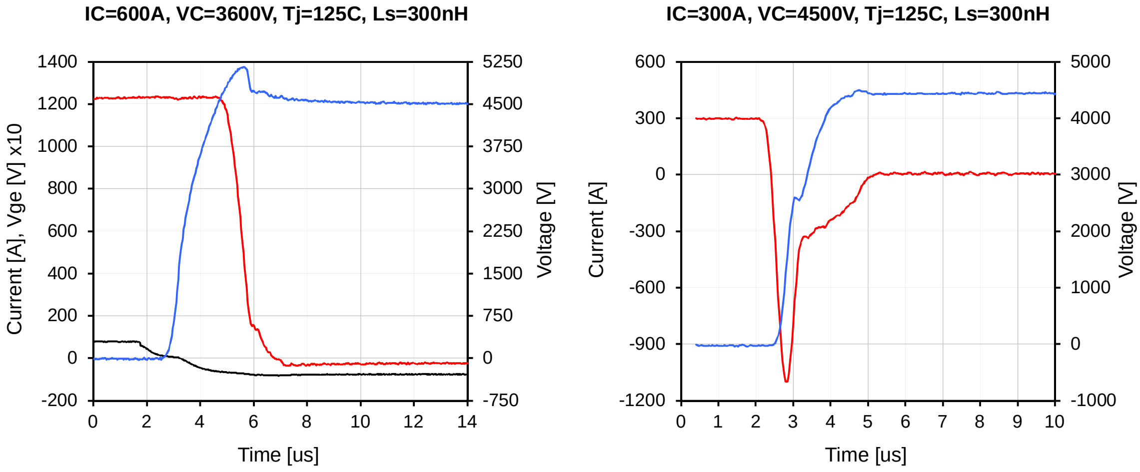

Fig. 7. 6.5kV/600A BIGT HiPak1 IGBT-mode turn-off waveforms under SOA conditions and demonstration of diode softness

3.4. Diode surge current

The diode anode (emitter) of the BIGT is produced by a fine pattern of P-well profiles for obtaining low injection efficiency for improved diode performance during switching operation. This design of the diode is known to perform worse under surge conditions compared to highly doped and deep anodes of conventional diodes. However, in the BIGT module, the surge is shared among all the chips, giving an area increase by a factor of 3 compared to the standard HiPak module (IGBT:diode ratio 2:1). Therefore, despite the reduced surge capability per chip, the surge current of the complete module is not compromised. Figure 8 shows the last pass measurement of the diode surge current test for one HiPak substrate. The substrate with 6 BIGT chips and rated nominal current of 150A, reaches 3000A before the destruction occurs, detected as a gate-emitter short. Consequently, the BIGT HiPak1 module has a higher diode surge rating than a larger footprint conventional IGBT/diode HiPak2 module. The BIGT HiPak2 module is expected to go well beyond that and offer record breaking surge currents for this voltage class.

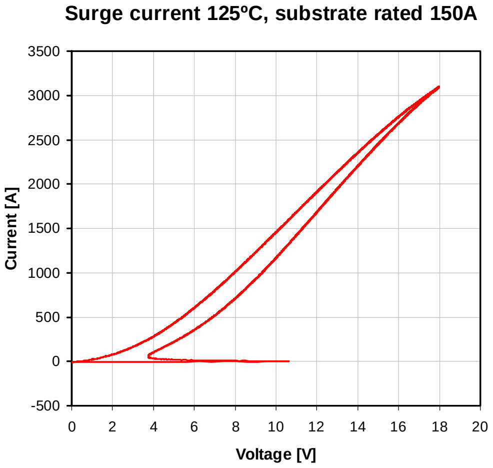

Fig. 8. Surge current capability of one 6.5kV/150A BIGT HiPak substrate

4. Optimization of losses though MOS control

4.1. MOS control

As already mentioned earlier in the paper, the diode mode plasma distribution in the BIGT device can be controlled by the gate voltage. Applying a positive gate voltage establishes the MOS channel between the emitter contact and the n-base, acting as a path for electrons, similar to the anode shorts. As the MOS channel shorts the p-well, the hole injection is reduced and the plasma concentration near the emitter is lowered. Setting the gate voltage negative again removes the MOS channel and restores the high plasma concentration near the emitter, see Figure 9 a). In this way the plasma shape can be adjusted by the gate control enabling operation of the module on a better technology curve for particular mode of operation.

Figure 9 b) shows the gate pulse patterns during the diode turn-off. In a standard non-optimized approach, the gate voltage is kept positive during the diode conduction, which in the BIGT case leads to an increase of diode conduction losses. Furthermore, the blanking time t_{bl} before the switching is in the order of 10 μs during which the plasma concentration is increasing at the emitter causing higher switching losses. The switching losses can be adjusted by shortening the blanking time.

In the optimized MOS control pattern the gate voltage is kept negative during the diode conduction phase for the low on-state losses. Before the switching, the gate voltage is temporarily raised above the threshold for the time t_g to reduce the plasma concentration near the emitter and lower the switching losses. This method is most effective when the blanking time is short and the gate pulse t_g is sufficiently long to allow the plasma concentration to adjust accordingly.

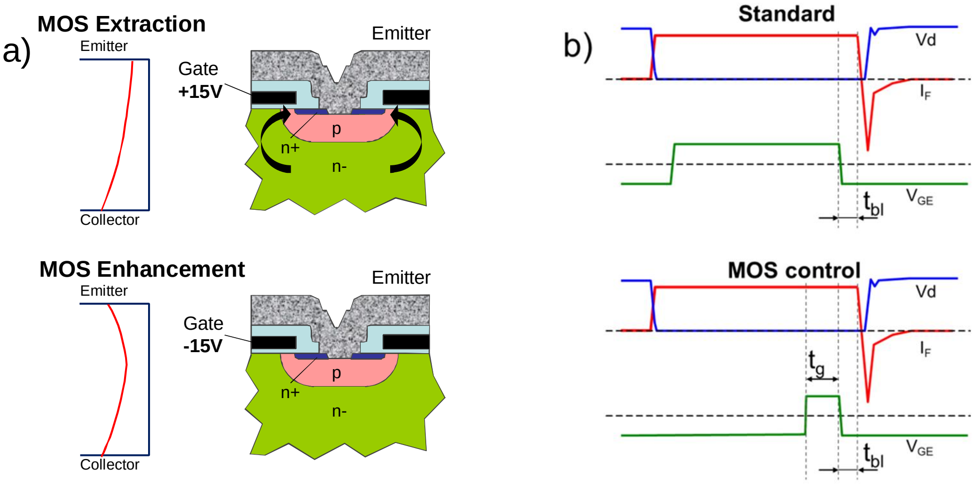

Fig. 9. a) Optimizing the plasma shape near the emitter by gate control.
b) Gate pulse patterns during diode conduction and switching

4.2. Optimization of losses in 6500V HiPak1 BIGT module

Figure 10 shows the dependency of the diode recovery and IGBT turn-on losses as a function of the gate pulse t_g and blanking time t_{bl}. As visible from the decay rate of the curves, a gate pulse t_g in excess of 50 µs is required to achieve the lowest concentration of the carrier plasma at the emitter (lowest switching losses). To prevent the rise of the plasma concentration again before the switching, the blanking time must be adjusted below 5 µs. Keeping the gate always negative ensures low conduction losses, but the switching losses are increased by 20-30%, as indicated with the points at $t_g = 0$ µs.

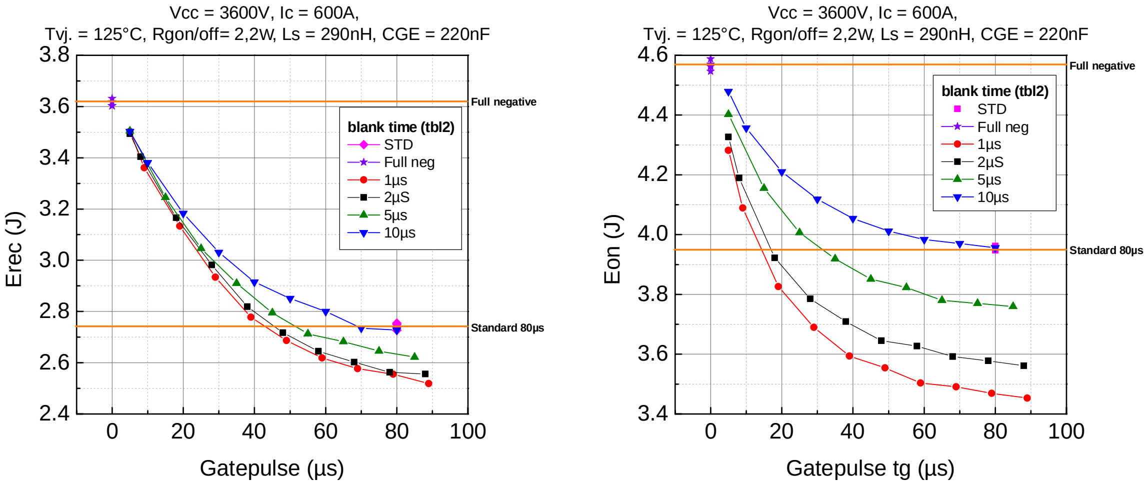

Fig. 10.: Effect of different gate pulses before the diode turn-off on the E_{rec} and E_{on} losses

5. Conclusions

The BIGT technology will provide a potential solution for future high voltage applications demanding compact systems with higher power levels, especially those with high diode current requirements which are beyond the capability of the standard two-chip approach. This paper presented the latest results for the 6500V/600A BIGT HiPak1 modules showing the possibility of reaching current ratings of 900A in the future with 6500V BIGT HiPak2 modules.

6. Literature

[1] H. Takahashi et al.; "1200V Reverse Conducting IGBT" Proc. ISPSD’04, p 133.
[2] H. Ruthing et al.; "600V RC-IGBT for Drives Applications in Ultra-Thin Wafer Technology" Proc. ISPSD’06, p 89.
[3] M. Rahimo, U. Schlapbach, A. Kopta, J. Vobecky, D. Schneider, S. Klaka: “The Bi-mode Insulated Gate Transistor (BIGT) A Potential Technology for Higher Power Applications” ISPSD, Barcelona, Spain, 2009.
[4] M. Rahimo et al.; "A High Current 3300V Module Employing RC- IGBTs Setting a New Benchmark in Output Power Capability" Proc. ISPSD’08, p 68.
[5] M. Rahimo et al.; "Realization of Higher Output Power Capability with the Bi-Mode Insulated Gate Transistor (BIGT)", EPE’09.
[6] A. Kopta, M. Rahimo, R. Schnell, M. Bayer, U. Schlapbach, J. Vobecky; “The Next Generation 3300V BIGT HiPak modules with current ratings exceeding 2000A” Proc. PCIM 2010, p 464.
[7] Hans-Günter Eckel; "Potential of Reverse Conducting IGBTs in Voltage Source Inverters" Proc. PCIM 2009, p 334.
[8] L. Storasta, M. Rahimo, M. Bellini, A. Kopta; “The Radial Layout Design Concept for the Bi-Mode Insulated Gate Transistor” ISPSD, San Diego, USA, 2011