SPT+, the Next Generation of Low-Loss HV-IGBTs

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Abstract:
Following the successful introduction of the high voltage Soft-Punch-Through (SPT) IGBT range, we introduce in this paper our next generation of HV-IGBTs employing the newly developed SPT^+ technology. The new IGBTs exhibit significant loss reduction in terms of on-state and turn-off losses while maintaining smooth switching waveforms and the extreme SOA performance characteristic of the well-established HV-SPT IGBTs.

Introduction

Until recently, the trench concept was considered the only possibility to obtain a significantly improved performance with respect to currently available IGBTs. We now demonstrate for the first time for the 3300V IGBT voltage class, that a high performance IGBT with much lower losses can be realised using an enhanced planar cell design combined with the well-established Soft-Punch-Through (SPT) concept. We have named the newly developed low-loss technology "SPT^+".
The correlation obtained by plotting turn-off losses versus on-state voltage, strongly depends on the manufacturing technology (i.e. "technology curve"). Therefore, a simultaneous reduction of both parameters can only be achieved by an improved cathode and silicon design. The $V_{CE(SAT)}$ of the new SPT^+ IGBT shows approximately a 25% reduction in on-state losses compared to the SPT-IGBT while keeping low E_{off} values as shown in Figure 1.

The loss trade-off performance of the new SPT^+ IGBT technology is comparable to that achieved using trench technology. However, an enhanced planar structure was chosen in order to maintain the high levels of ruggedness associated with the planar technology as presented in a previous publication [1]. The results presented in this paper show that despite the low on-state and switching losses of the SPT^+ IGBT, the high levels of short-circuit withstand capability and world-class turn-off ruggedness of the current generation have been. In addition, the Soft-Punch-Through structure ensures good switching controllability and soft turn-off waveforms. We examine the design and key characteristics of the new 3300V SPT^+ IGBT as well as the application of the new IGBT in the HiPak 3300V/1200A standard and high-insulation module range shown in Figure 2. This new benchmark in losses and SOA capability will provide high voltage system designers with simplified cooling and enhanced ratings while maintaining the newly acquired robustness of HV SPT.

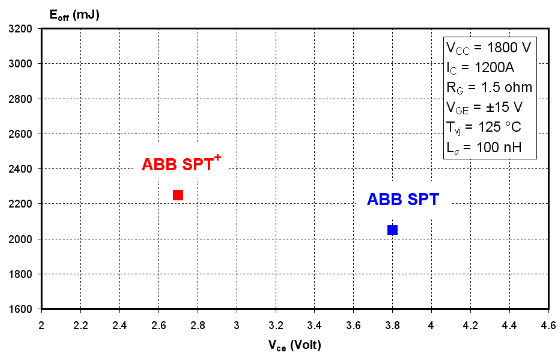

Figure 1: New 3300V/1200A SPT^+ IGBT HiPak technology benchmark

Figure 2: The HiPak standard (left) and high-insulation (right) modules with 3300V SPT^+ IGBT technology.

SPT+ IGBT Chip Technology

The next generation 3.3kV SPT+ IGBT chip was specifically designed to substantially reduce the on-state losses while maintaining low levels of switching losses. However, this approach had to be combined with a carefully selected trade-off between losses, high levels of dynamic SOA capability, high immunity against cosmic ray induced failures and smooth switching behaviour.
The new SPT+ platform exploits an enhanced carrier profile technique through cell optimisation, which is compatible with our advanced and extremely rugged planar cell design. In addition, a newly optimised 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 collector current to smoothly decrease during the turn-off transient, hence, the term “Soft” in SPT. Thanks to the combination of an enhanced cell design and thin wafer, the new 3.3kV SPT+ IGBT has enabled us to reach a new benchmark in the technology curve. The new SPT-buffer, in combination with an optimal anode design, further ensures good short-circuit controllability with a high Short Circuit Safe Operating Area (SCSOA).

3300V/1200A SPT+ IGBT HiPak Module Electrical Performance

The static and dynamic characteristics of 3300V/1200A HiPak modules with the new low loss SPT+ IGBT chips are evaluated and the results presented below.

a) Static Characteristics:

In order to demonstrate the normal IGBT behaviour of the new technology, we first present in Figure 3 the output characteristics at different gate voltages for the 3300V/1200A module at 125°C. The combination of the new SPT+ enhanced IGBT cell design and reduction in the base region thickness have resulted in 25% less on-state losses compared to current SPT structures. We report for a 3300V/1200A IGBT module a typical on-state voltage at rated current of 2.2V at 25°C and 2.7V at 125°C. These values were obtained at chip level at a current density of 50A/cm^2. The on-state characteristics measured at module level are shown in Figure 4.
In addition to the extremely low on-state losses, the curves exhibit a strong positive temperature coefficient even at low current levels. This feature is crucial for parallel operation of chips as well as modules especially with high current ratings such as in the HiPak range to avoid any current mismatch between the paralleled devices. The freewheeling diodes employed in the SPT+ HiPak module also maintain low on-state voltages and a slightly positive temperature coefficient having 2.3V at 25°C and 2.35V at 125°C at rated current.

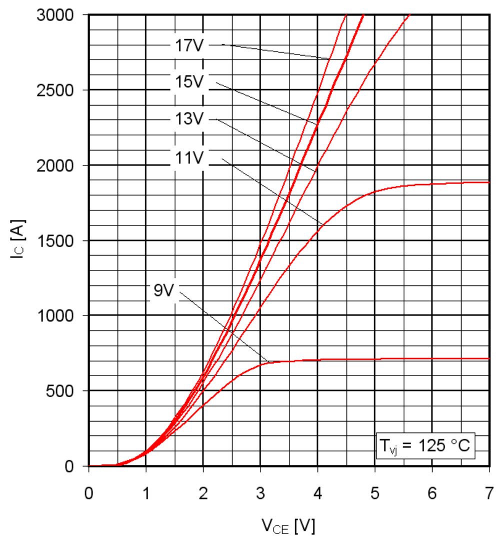

Figure 3: 3.3kV/1200A SPT+ IGBT HiPak output characteristics at 125°C

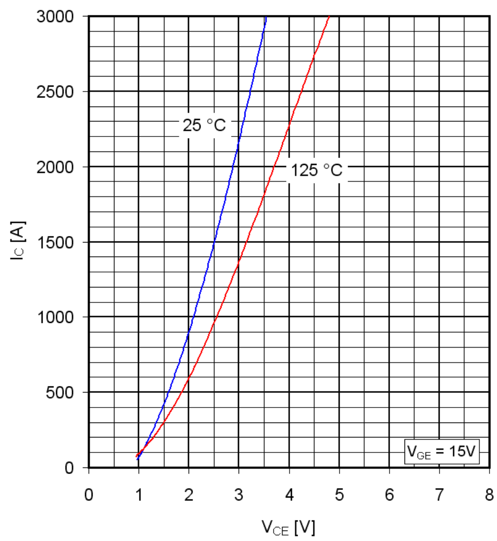

Figure 4: 3.3kV/1200A SPT+ IGBT HiPak on-state characteristics at 25°C and 125°C

b) Switching Characteristics:

Figure 5 shows the turn-off switching characteristics under nominal conditions for the 3300V/1200A SPT+ IGBT HiPak module. The tests were carried out at a nominal current of 1200A and a DC-link voltage of 1800V at 125^{o}C.

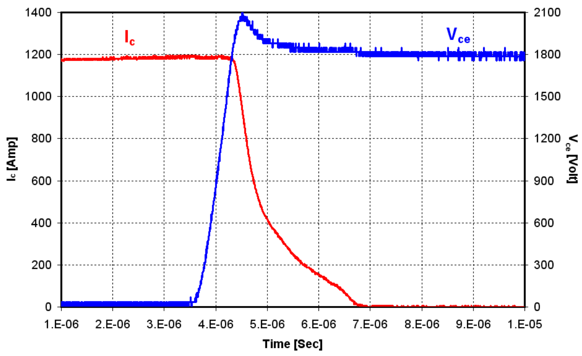

Figure 5: 3.3kV/1200A SPT+ IGBT HiPak turn-off waveforms at 125°C
V_{cc}=1800V, I_c=1200A, V_{ge}=15V, R_g=1.5Ω, L_s=100nH

As can be seen in Figure 5, the current switching transients of the 3300V SPT+ IGBT maintain very smooth waveforms with a short current tail having no snap-off effects. This behaviour is due to the SPT buffer region and the optimal silicon wafer specification. Since less excess carriers need to be extracted, the tail duration of the current is short and therefore turn-off losses E_{off} can be kept low at a value of 2.25 Joules Therefore, a perfect balance is achieved resulting in fast switching speeds with low losses, short tail current, low overshoot voltage and low EMI levels.

Figure 6 shows the turn-on switching waveforms under the same nominal conditions. The IGBT and diode were designed for low turn-on switching losses E_{on} thanks to an optimised design of the 3300V diode and low IGBT input capacitance for faster V_{ce} fall times. The turn-on losses have typical values of 1.7 Joules under nominal conditions at 125°C and a di/dt value of 6000A/µsec using a gate resistance value of 1.5 ohms. The turn-off and turn-on energy losses of the SPT+ IGBT are plotted as a function of the collector current and gate resistance as shown in Figure 7 and Figure 8 respectively.

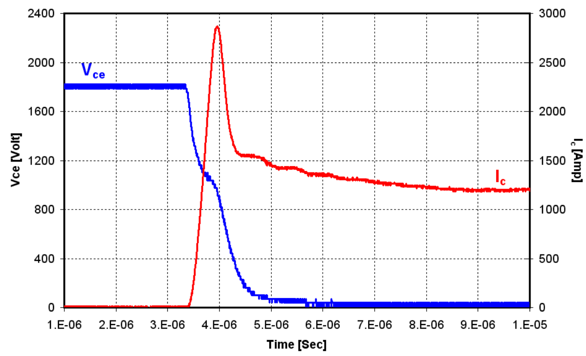

Figure 6: 3.3kV/1200A SPT+ IGBT HiPak turn-on waveforms at 125°C
V_{cc}=1800V, I_c=1200A, V_{ge}=15V, R_g=1.5Ω, L_s=100nH

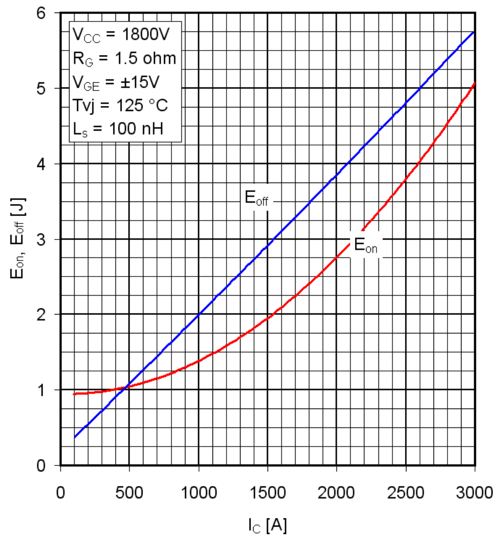

Figure 7: 3.3kV/1200A SPT+ IGBT HiPak
E_{on} and E_{off} vs. I_c losses curves

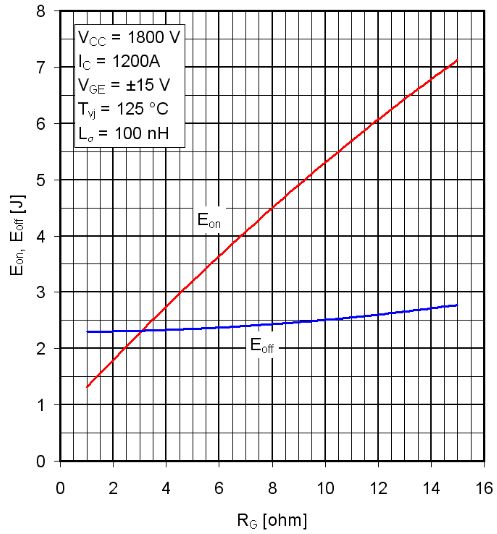

Figure 8: 3.3kV/1200A SPT+ IGBT HiPak
E_{on} and E_{off} vs. R_g losses curves

In order to confirm the soft switching performance of the new module, a turn-off test at nominal current was conducted with a much higher stray inductance of 270nH at 125°C. The DC-link voltage was also increased to 2000V. Even under such conditions, the turn-off current showed no oscillations with only a small increase in voltage associated with a current drop during the tail phase as shown in Figure 9.

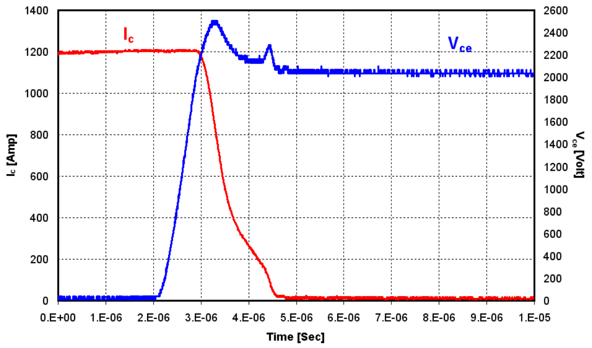

Figure 9: 3.3kV/1200A SPT+ IGBT HiPak turn-off waveforms at 125°C
V_{cc}=2000V, I_c=1200A, V_{ge}=15V, R_g=1.5Ω, L_s=270nH

c) *SOA Performance:*

In order to evaluate the SOA performance of the new 3300V SPT+ IGBT technology, the module was subjected to a wide range of switching tests under extreme conditions in terms of current, voltage and stray inductance. The main aim of these measurements was to confirm that the SPT+ IGBTs could still maintain the world-class performance associated with HV-SPT technology presented previously. No active clamps or snubbers were employed in the test.
Initially we needed to confirm the extremely high turn-off current capability and SSCM of a single 50A IGBT chip as shown in Figure 10. The device was capable of turning-off more than 7 x nominal current at 360A with a DC link voltage of 2700V at 125°C.
Figure 11 and Figure 12 show the (RBSOA) switching characteristics of the 3300V/1200A SPT+ IGBT HiPak module during turn-off and turn-on respectively. The modules were tested at a current of 4000A and DC-link voltage of 2500V at 125°C. A peak overshoot voltage of 3250V can be seen during the turn-off period.

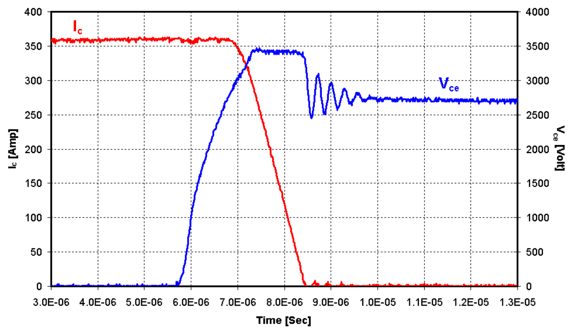

Figure 10: 3.3kV/50A SPT+ IGBT Chip turn-off SOA waveforms at 125°C with "SSCM"
V_{cc}=2700V, I_c=360A, V_{ge}=18V, R_g=33Ω, L_s=2.4uH

A 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. Rugged performance is also demonstrated during turn-on for both the IGBT and diode. Turn-on waveforms show a di/dt current ramp of 9000 A/µsec and a peak current of 6000A.

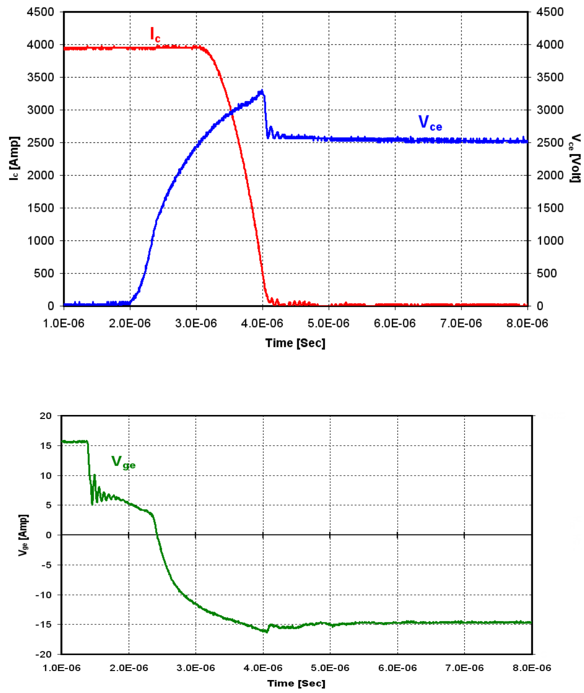

Figure 11: 3.3kV/1200A SPT+ IGBT HiPak turn-off SOA waveforms at 125°C
V_{cc}=2500V, I_c=4000A, V_{ge}=15V, R_g=1.5Ω, L_s=100nH

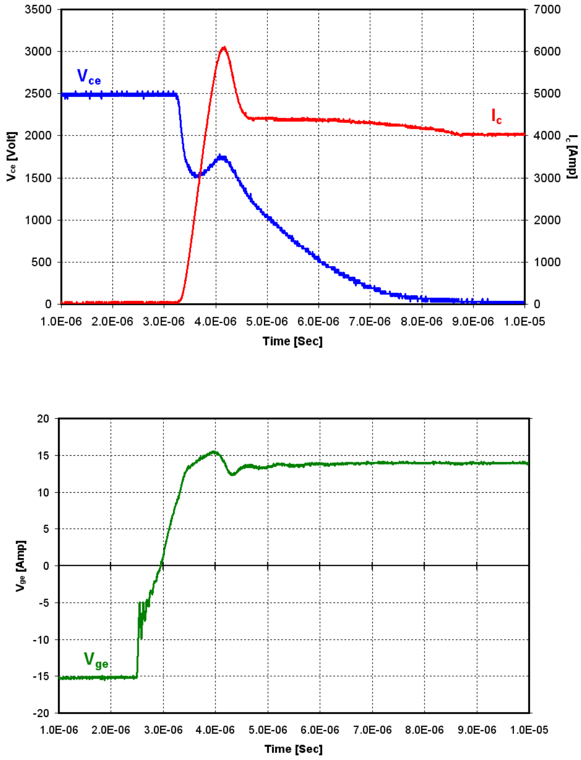

Figure 12: 3.3kV/1200A SPT+ IGBT HiPak turn-on SOA waveforms at 125°C
V_{cc}=2500V, I_c=4000A, V_{ge}=15V, R_g=1.5Ω, L_s=100nH

Further tests were carried out to determine the Switching-Self-Clamping- Mode “SSCM” capability of the SPT+ IGBT HiPak module [2]. Then 3300V71200A module was tested at 125°C with a higher than standard stray inductance value of 270nH and up to four-times nominal current at a DC-link voltage of 2600V. The module comfortably withstood these conditions as shown in Figure 13.

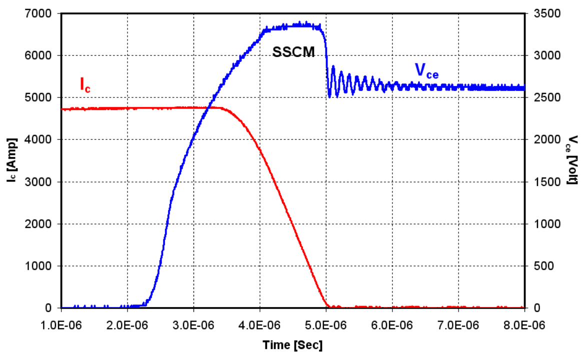

Figure 13: 3.3kV/1200A SPT+ IGBT HiPak turn-off SOA waveforms at 125°C with “SSCM”
V_{cc}=2600V, I_c=4800A, V_{ge}=15V, R_g=1.5Ω, L_s=270nH

The total energy dissipated during turn-off was 22 Joules with a peak power dissipation of 13MW. Successful operation in SSCM was obtained with a self-clamp voltage of 3400V. The duration at which the device remained in SSCM was approximately 1µsec. By enabling the IGBT module to withstand SSCM, the device will exhibit a square SOA capability up to the self-clamp voltage level. The associated square SOA I/V curve is shown in Figure 14. The high dynamic ruggedness, combined with 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.

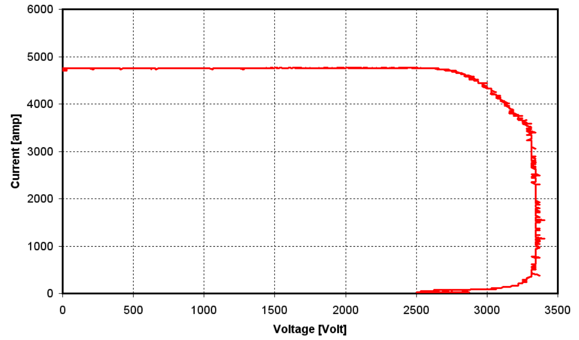

Figure 14: 3.3kV/1200A SPT+ IGBT HiPak I/V square RBSOA curve.

d) *Short Circuit Performance:*

The high short-circuit capability of the new SPT+ IGBT was also demonstrated at 25°C and 125°C as shown in Figure 15 and Figure 16 respectively. The waveforms show the 3300V/1200A HiPak module in short-circuit mode at a DC rail voltage of 2500V for a current pulse of 10µsec.
Controllable and clean current waveforms were obtained exhibiting no parasitic oscillations thanks to the combination of an optimal IGBT chip and internal module layout. The current waveform shows a reasonable average short-circuit current of approximately 7000A at 125°C and 8000A at 25°C. The SPT buffer and anode designs employed in the 3.3kV SPT+ 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 gate drive voltage of 15V.

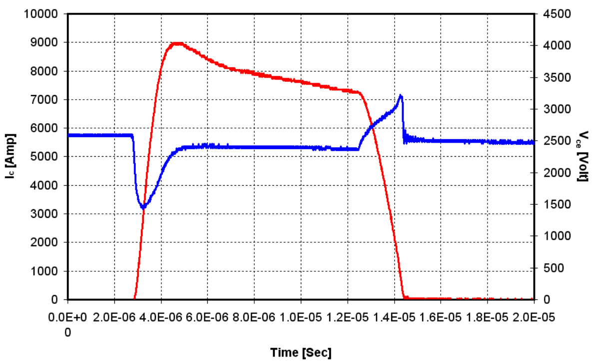

Figure 15: 3.3kV/1200A SPT+ IGBT HiPak SCSOA waveforms at 25°C

V_{cc}=2500V, I_{sc}=8000A, V_{ge}=15V, R_g=1.5Ω, L_s=100nH

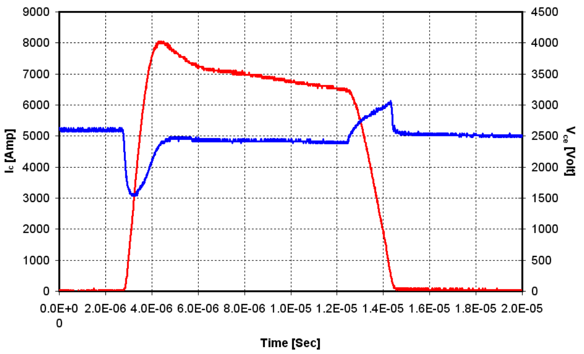

Figure 16: 3.3kV/1200A SPT+ IGBT HiPak SCSOA waveforms at 125°C

V_{cc}=2500V, I_{sc}=7000A, V_{ge}=15V, R_g=1.5Ω, L_s=100nH

3300V/1200A SPT+ IGBT HiPak Module Frequency Performance Chart

Figure 17 shows a calculated curve for the inverter output current against the switching frequency at 125°C for the new low-loss SPT+ 3.3kV IGBT HiPak module compared to the current generation HV-SPT.

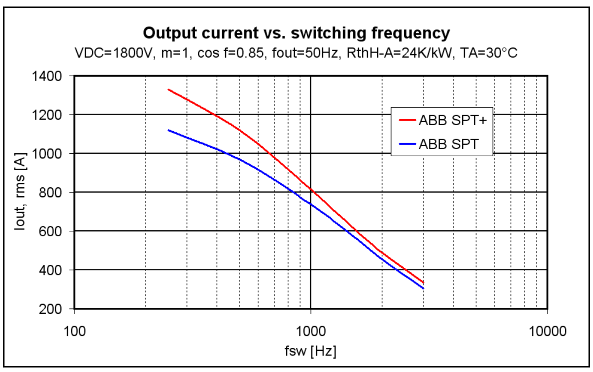

Figure 17: Inverter output current vs. Frequency for 3300V/1200A modules

The SPT+ curve shows a clear increase in output current capability over the whole range of switching frequencies. Without any changes to the inverter design except the use of SPT+, the output current can be increased by 10%-20% within a switching frequency range from 250Hz up to 1000Hz in a typical forced-air cooled application.

Conclusions

Compared to existing state-of-the art 3300V SPT IGBTs, the newly developed SPT+ IGBT from ABB offers 25% lower on-state losses while still maintaining low turn-off losses, thereby setting a new benchmark for 3300V IGBT performance. HV-SPT+ achieves the same extreme ruggedness during switching and short-circuit conditions and offers the same low EMI levels as current HV-SPT. The electrical characteristics of this next generation were presented for the case of a 3300V/1200A HiPak module thereby establishing that planar technology can match trench technology in terms of losses while maintaining its SOA superiority.

This new technology will undergo minor optimizations, which may result in further improvements by the time of its release. Products with SPT+ will be commercially available in 2006 in several voltage classes.

References

1. M. Rahimo et al., “2.5kV-6.5kV Industry Standard IGBT Modules Setting a New Benchmark in SOA Capability” Proc. PCIM’04, NURNBERG, GERMANY, 2004.
2. M. Rahimo et al., "Switching-Self-Clamping-Mode “SSCM”, a breakthrough in SOA performance for high voltage IGBTs and Diodes" ISPSD'2004, JAPAN, May 2004, pp 437-440.