Soft Punch Through (SPT) – Setting new Standards in 1200V IGBT

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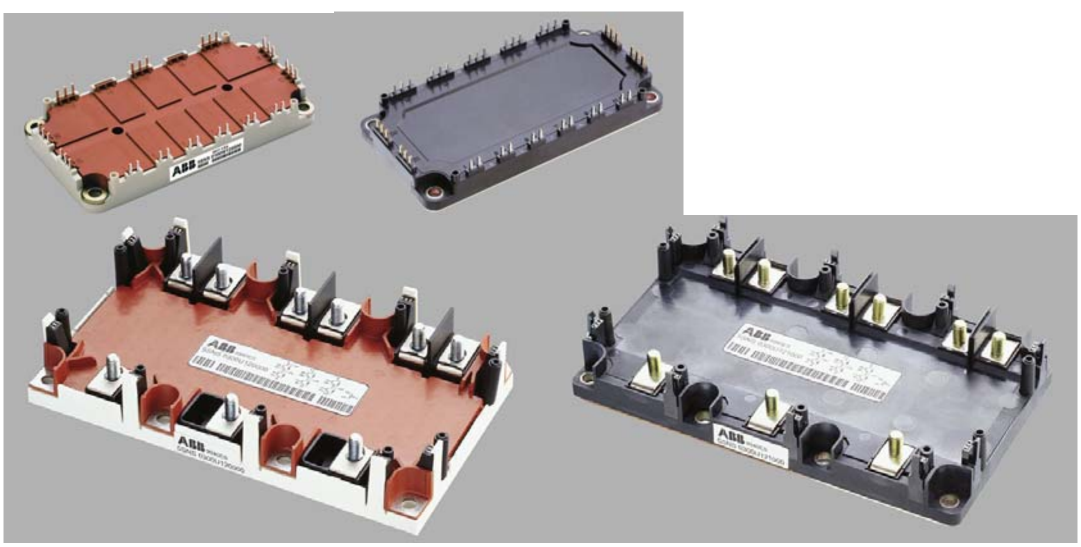
Abstract

The industrial drives market continues to show dynamic growth and tough competition. The players in this market use all their ingenuity in order to find competitive advantage wherever possible. Part of this competitive advantage comes from close interaction with their suppliers: of passive components, mechanics, control electronics and, of course, IGBT modules.
When searching for competitive advantage the IGBT can be decisive, because a number of its characteristics define the critical parameters for the system design.
This paper introduces a new 1200V IGBT from ABB Semiconductors: the Soft Punch Through (SPT). This line-up of dies is used in the LoPak module range. The new chipset demonstrates ruggedness, low-losses, good parallelabilty and soft switching edges. In addition the chip layout has been carefully designed to allow very efficient and simple module construction without the need for internal chip paralleling resistors, with a very large bondable area and corner gate.

Introduction

The 1200V IGBT market has become one of the most competitive areas of power electronics in recent years. The decisiveness of the IGBT module choice in the inverter manufacturer's search for competitive advantage has led to great efforts to produce optimised chips and packages (Refs. 1, 2, 3). As in most electronics sectors customers have high expectations in terms of device performance improvement, but additionally the aggressive inverter marketplace tends to pass on cost down requirements to the IGBT suppliers. Despite these efforts, until recently the performance improvements in 1200V IGBT modules had levelled off. An on-state voltage of just under 3V at 125^{o}C had become relatively uniform state-of-the-art amongst suppliers of devices with relatively low switching losses. The introduction of trench devices (Refs. 4, 5) has improved significantly on these figures, but has brought with it a number of other possible disadvantages or risks, such as cost, ruggedness, high input capacitance, high thermal resistance, difficulty to parallel connect, etc. With the introduction of SPT from ABB Semiconductors the losses of trench devices have been achieved with a planar technology which has none of these disadvantages.

Fig.1 LoPak3 and LoPak5 Baseless and Copper Based Versions

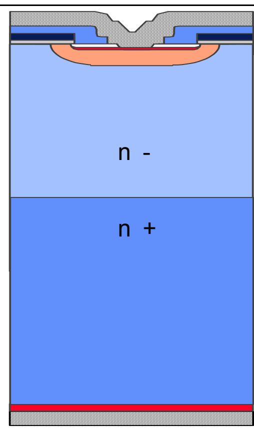
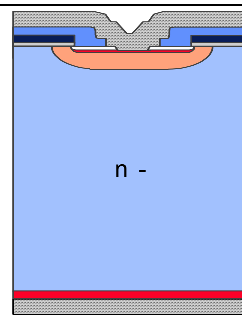
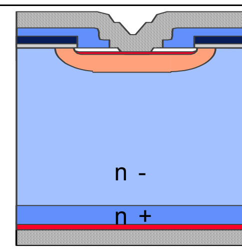


This paper will examine the key characteristics of the SPT IGBT in detail as well as the application of the dies in the new LoPak standard module line-up. Particular reference will be made to the benefit for the end user of each of these characteristics and how competitive advantage can be achieved in the system by application of these components.

Punching Through… but Softly (SPT)

There is a lively discussion between semiconductor physicists and engineers about the accuracy of the terms Punch Through (PT) and Non-Punch Through (NPT) when applied to IGBT design. Independent of the merits of this debate the name PT has become accepted as the label for relatively thick IGBT chips made from epitaxial wafers and containing an N+ buffer (or Field Stop) layer. In the same way the term NPT has become the label for thinner chips made from cheaper FZ (float zone) wafers, which do not have the additional N+ layer.
This may all seem a little academic to users of the devices, however there are well know differences between the performance of the two technologies, which are highlighted as part of Fig.2. A further reason for the growth in the popularity of NPT is that the cost of the wafers used (FZ) is significantly lower than that of the PT type (epitaxial wafers). When planning the introduction of the new SPT 1200V generation it was, therefore, very important for ABB to select the best parameters from each of the PT and NPT technologies and combine them in one new device. But it was equally important to ensure that this could be achieved using the lower cost FZ wafers.

Fig.2 PT, NPT and Soft Punch Through (SPT) Technologies

	Punch Through (PT)	Non - Punch Through (NPT)	Soft Punch Through (SPT)
Structure			
Features	Some devices show snappy turn-off at high V_{DC}	Positive temperature coefficient of on-state Extremely rugged	Positive temperature coefficient of on-state Extremely rugged Low losses
Material	Epitaxial	Float Zone	Float Zone

SPT Design Goals

The development process for SPT was started by discussions about what would be the ideal switching waveform for an IGBT. This is not so obvious as it first seems. Most of us drew a current square wave to start with. Although this is ideal from the point of view of switching losses, when thinking about the circuit effects of such a waveform in more detail it is clear that such high dI/dt levels will cause enormous voltage overshoots with even small stray inductance in the circuit. With a trapezoidal current shape where the turn-off dI/dt is linear then this problem is resolved and the current gets from full value to mininum in the fastest possible time within the limits of the voltage overshoot which is acceptable. However this is also too simple as the square edges of such a waveform generate unpleasant harmonics, which would negatively impact the EMC performance of the system and generate high levels of dV/dt. This means a rounding of the waveform is needed. Too much rounding compromises switching losses however.

Fig.3. Evolution of the ideal Switching Waveform

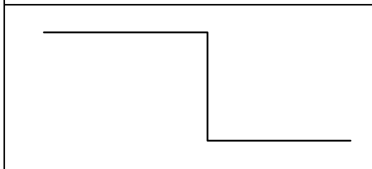
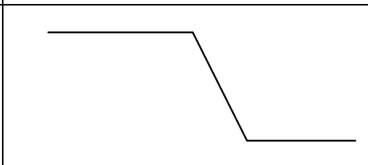
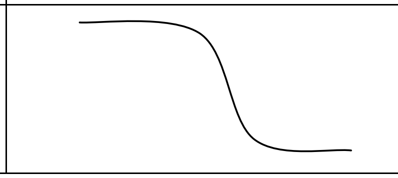
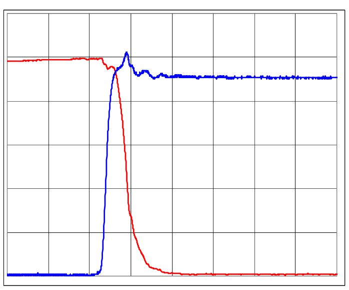
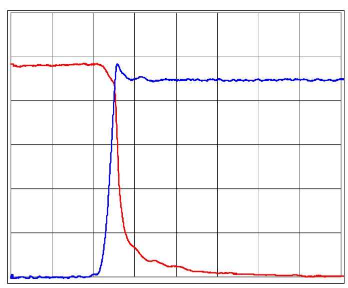
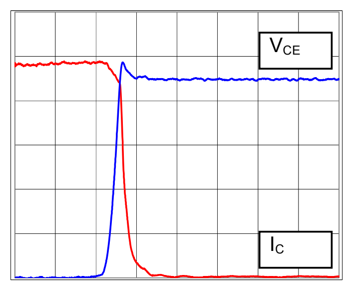
Square wave Collector Current Zero switching loss but Infinite dI/dt causes high overvoltages	**Trapezoidal Collector Current** Constant dI/dt during turn-off. Slope defines switching loss and overvoltage in circuit. Square edges (high dI^2/dt^2) cause high dV/dt and EMC problems	**Smoothed Trapezoidal** Smoothing removes the problems of trapezoidal shape but adds to switching loss. So tail current must be short
		

Fig.4 Typical Switching Waveforms of 100A 1200V PT, NPT and SPT devices switching 900V DC, 125°C with 60nH DC Link inductance. (I_C 20A/div. V_{CE} 200V /div. 500ns/div.)

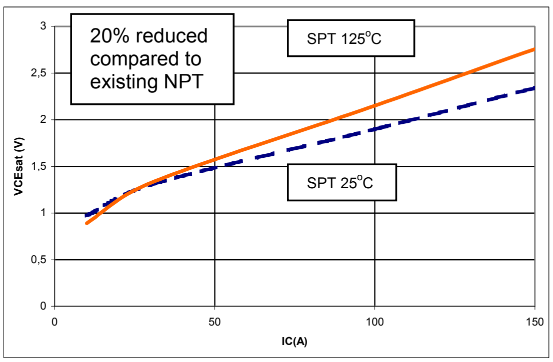
Punch Through (PT) (Test device shown for purpose of comparison)	Non-Punch Through (NPT)	Soft Punch Through (SPT)
		
• Voltage overshoot as field hits field-stopping buffer layer, under high voltage conditions. • High dV/dt during voltage rise • Current tail at high level but for short time • Current tail temperature dependent	• Low voltage overshoot • Linear voltage rise • Relatively long, but low tail current • Under some switching conditions sharp transition between current fall and tail phases (not visible in this plot)	• Lowest voltage overshoot • Linear voltage rise • Low and short tail current with extremely low losses • Soft transition between fall and tail phases

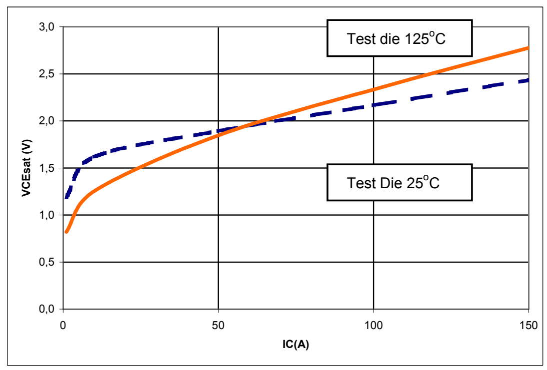
Comparing figures 3 and 4 it is clear that the SPT device approaches the “ideal” switching waveform. Furthermore the softness of switching achieved by the SPT devices allows a significant improvement in the EMC performance of the system which can lead to major system cost savings, by reducing the system screening and filtering requirement. The voltage rise time is relatively well controllable by choice of turn-off gate resistor. Since the SPT voltage rise is so linear with time then the dV/dt applied to motor isolation and the output of the system is as low as can be achieved for a given switching loss.
The soft, short and low current tail of the SPT device is key in reducing switching losses (see section on SPT switching characteristics and Fig. 9a).

SPT On-State Characteristics

Figure 5a) shows the on-state characteristic of the SPT 100A die. The fist point to make here is that the value achieved is a reduction of 20% compared to the existing NPT product. For comparison purposes a different shape of on-state is shown in 5b) for a test device fabricated by ABB, having the same value at nominal current, 125^{o}C, but higher at lower currents and also a negative temperature coefficient. This calculation serves to illustrate the importance of the temperature coefficient of on-state and the resistive characteristic demonstrated by the SPT die.
Although both die have the same $V_{CE(SAT)}$ at 125^{o}C, nominal current, a calculation of the on-state losses they generate in a naturally sampled PWM inverter with 75A rms. gives very different results. Since the SPT die has lower on-state at lower currents then it generates lower loss for most of the output sinewave cycle of the system. So the SPT die in this case produces 34W of on-state loss and the test die 36W.
Furthermore if we consider that the system will actually not run with a junction temperature of 125^{o}C most of the time, but perhaps at (say) 90^{o}C, then the effect of the device temperature coefficient further increases the difference between the losses in the two dies. With the 90^{o}C junction temperature considered the SPT die losses are reduced due to 33W, whereas the test die losses increase to 37W.

Figure 5. On-State Voltage against collector current a) SPT 100A 1200V LoPak3, b) Test die with less resistive characteristic and negative temperature coefficient for comparison purposes.



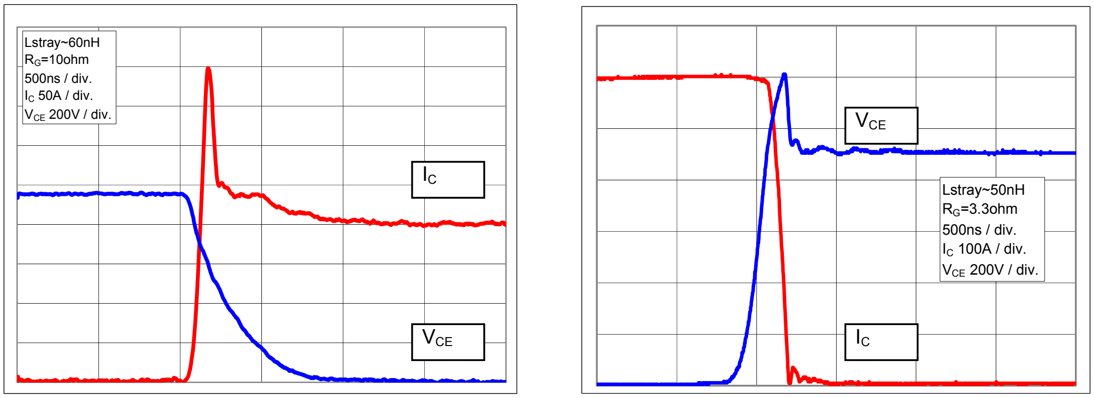


The positive temperature coefficient and resistive on-state characteristic are also very important for parallel connecting chips and modules. The die in Fig. 5b) would parallel connect poorly due to the very steep diode-like characteristic. If there is any slight mismatch in voltage drop across dies, it is “amplified” by the slope of the curve, causing a more significant current mismatch. The positive temperature coefficient of on-state of the SPT works as a negative feedback mechanism to improve sharing, should there be any mismatch in voltage drop across parallel connected dies. Furthermore since SPT dies are not particle irradiated for carrier lifetime killing the spread of characteristics is also very narrow. In this way die parallel connection is made much easier.
In addition to the excellent sharing of the IGBTs the ABB 1200V MPS diodes used in the LoPak series have a positive temperature coefficient, improving not only IGBT but also diode current sharing. (Ref. 1, 6)

SPT Ruggedness

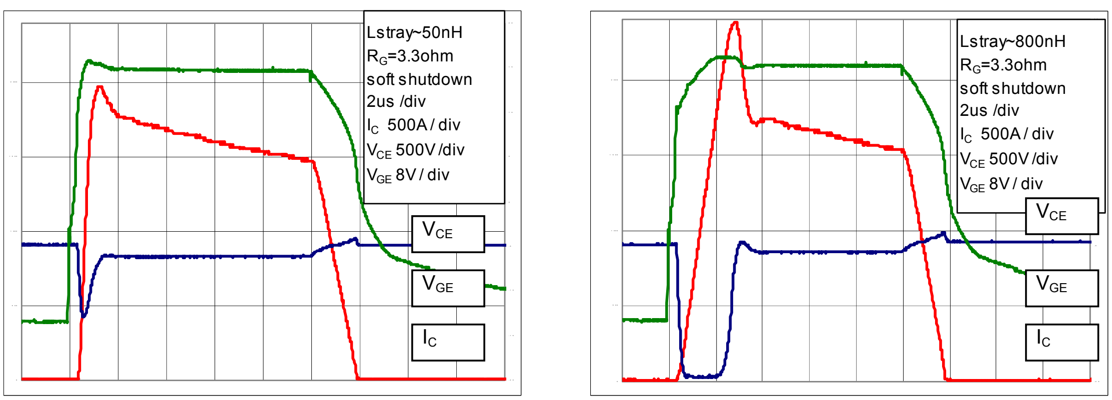
The SPT die is just as rugged as the well-known NPT technology. There is no need for additional costly or complex control circuitry to be built into the module in order to achieve this ruggedness. Figure 6a) shows the LoPak3 switching on into a freewheeling 100A load with 900VDC. Figure 6b) shows the RBSOA conditions of a LoPak5 switching off 600A at 900VDC and generating a 1200V peak.

Fig. 6 1200V SPT under SOA conditions. a) LoPak3 100A six pack at turn on into 200A on 900V DC, 125°C. b) LoPak5 300A six pack at turn off of 600A on 900V DC, 125°C.



The waveforms in Figs. 7a) and b) show the 300A 1200V LoPak5 device on a 900V DC link in short circuit with small series inductance and with significant load inductance respectively. The first waveform is representative of the case when one IGBT element in a phase leg fails or when there is a malfunction in the gating / control circuitry so that both devices in a leg are switched on simultaneously. Practically the short circuit with some load inductance (Fig. 8b) is more likely to happen in a real application. Unfortunately this is usually also the more severe case. As can be seen the short circuit current rise is limited by the load inductance until the IGBT begins to come out of saturation. As the voltage across the IGBT begins to rise charge is pumped through the reverse transfer (or Miller) capacitance of the device and begins to lift the gate voltage above the normal 15V level. The waveform shows that the gate reaches around 17V in this case, although internally on the IGBT side of the internal sharing resistors and gate inductance, it is likely to be higher. The increased gate voltage drives the IGBT harder on, further increasing the short circuit current. The cell design of the ABB IGBT allows for an exceptionally high ratio of input- to reverse transfer- capacitance, so that this IGBT is particularly insensitive to this effect and therefore easier to use in this critical short circuit mode.

Fig.7. LoPak5 300A 1200V SPT Six Pack under Short Circuit conditions on 900VDC link, 125°C. a) Short circuit 1. b) Short circuit with small load inductance

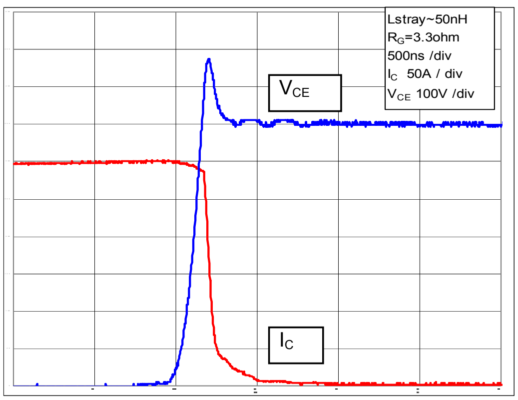


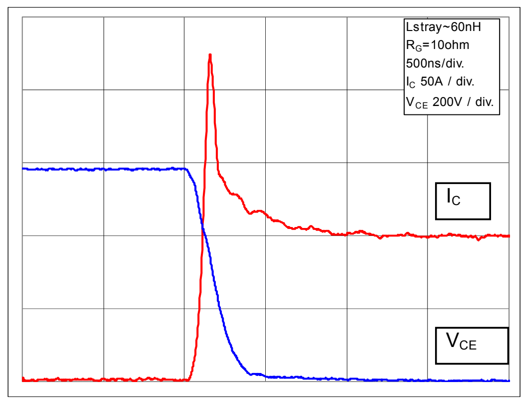
The rugged short circuit and SOA capability of the SPT die is intrinsic to the IGBT design itself and is not achieved by adding extra control circuitry inside the module. This keeps module cost down and means system manufacturers do not need additional components or cost in their assembles.

SPT Switching Characteristics

The soft switching characteristics of SPT were briefly mentioned in the introduction.
Fig. 8a) shows the turn-off of the IGBT with the typical SPT smooth and soft waveforms and short low tail current, which is relatively constant with temperature. A soft voltage waveform, with almost constant dV/dt during the voltage rise time, is achieved with a low overshoot.

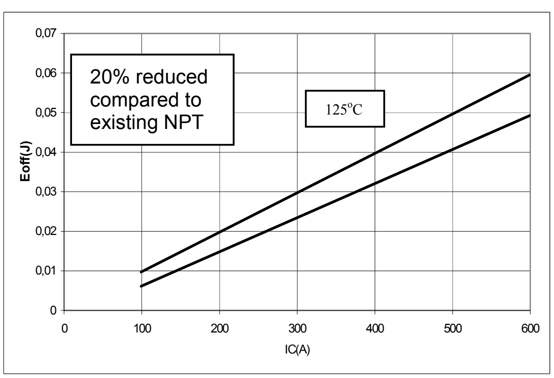
Figure 8. 1200V SPT Turn-off and Turn-on Waveforms
a) 300A LoPak5 six pack Turning off 300A on 700VDC link, 125°C,
b) 100A LoPak3 six pack Turning on into 100A on 600VDC link, 125°C,

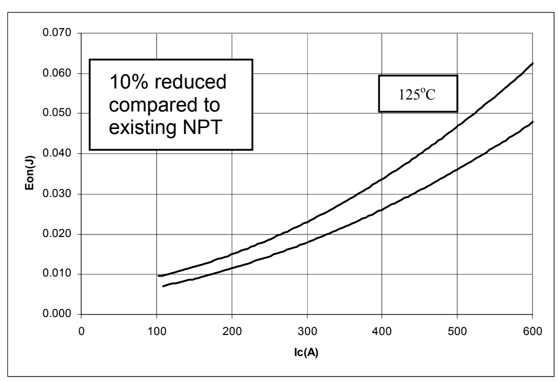




This results in turn-off switching losses of about 20% below the current NPT product. Fig. 8b) shows similar conditions at turn-on. Dynamically the diode has an exceptionally soft recovery characteristic even under low current and low temperature conditions, allowing the IGBT to be switched on with an unusually high dI/dt, minimising switching losses and deadtime requirements. In addition the switching losses achieved by the SPT turn-on are around 10% lower than those with the existing NPT devices, due to a faster fall of voltage during the diode recovery phase.

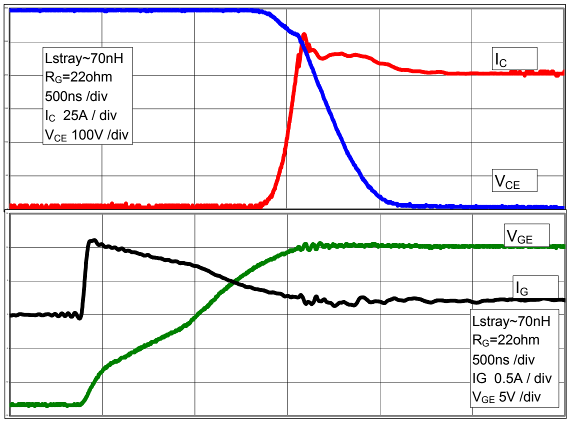
Fig. 9. Switching Losses SPT LoPak5 300A 1200V. (R_G = 3.3ohm, V_{DC} = 600V, fully integrated losses.)
a) Turn-off energy,
b) Turn-on energy





Gate Drive Requirements

Fig. 10. LoPak3 100A 1200V switching on at 600V 100A 25^{o}C.



The gate drive requirements of SPT are the same as for existing NPT devices. For example a 100A 1200V SPT die needs only 1μC of gate charge to switch 600V with a gate voltage of 0V to +15V. Even switching from a –15V gate supply only 1.5μC is required. As can be seen from Fig. 10 a driver with a pulse current capability of only 1A is sufficient to drive the 100A device. This means SPT can be implemented quickly into a design without the need for redesigning existing gate drives. Fig. 10 shows the typical gate characteristics when switching for the 100A 1200V LoPak3 six-pack.

Thermal Characteristics

Often the size of an inverter is determined by the amount of power that it needs to dissipate from internal losses to the air or other cooling system, without generating internal over-temperatures. We have already seen that the SPT IGBT generates very low losses, however this alone is not enough to ensure an efficient compact and reliable system. Another important factor is thermal resistance. For given losses the IGBT junction can be kept below the necessary limits only by an appropriate thermal resistance. This thermal resistance is the sum of the heatsink-to-air and that internal to the IGBT module (junction-to-case) plus any contact thermal resistance. It follows then that generally the lower the module thermal resistance then the smaller the heatsink can be and therefore the more compact the inverter can be.
By avoiding relatively expensive trench technology ABB Semiconductors can afford to put more Silicon into the same current rating of a chip and therefore achieve a much better value of thermal resistance than smaller trench chips.

LoPak

The line up of LoPak3, LoPak4, LoPak5 uses SPT technology in both baseless and Copper-based versions. To compliment the IGBT performance these modules include the 1200V MPS diodes (Ref. 6). These diodes have a positive temperature coefficient of on-state above around 90% of nominal rating and demonstrate extremely soft recovery characteristics. The modules themselves offer a high level of mechanical integration into the user's system, allowing extremely compact units to be built. In addition the principle of granularity and modularity allow fine steps of inverter power ratings to be manufactured using only 3 part numbers over a range of 50kVA to multi–MW. (Refs. 1,2,3)

Conclusion

SPT (Soft Punch Through) is a new planar IGBT from ABB Semiconductors. When compared to existing NPT technology, SPT reduces on-state losses by 20% and switching losses by 20% without increasing thermal resistance. SPT is specifically designed with parallel connection in mind and therefore has not only a positive temperature coefficient of on-state, but also a resistive characteristic. The technology does not need additional control circuitry to achieve ruggedness – it is just as rugged as existing NPT devices, and can be driven from the same drive circuitry. The uniquely soft turn-off waveforms are a major benefit to system manufacturers, particularly when requiring equipment to be EMC compliant.
These dies are combined with ABB Semiconductors' MPS diode in the LoPak module series.
Soft Punch Through – setting new standards in 1200V IGBT!

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