Optimization of High Voltage IGCTs towards 1V On-State Losses

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Abstract

The modern trends towards operating at lower switching frequencies in many power electronics applications adopting multi-level topologies, along with special demands for high current carrying capabilities and/or high efficiency, is forcing the development of application-specific devices. The Integrated Gate-Commutated Thyristor (IGCT) is an ideal device, which will lend itself well to these adaptations due to its inherent low conduction loss thyristor properties on the one hand, and the hard switched functionality on the other. Today however, IGCTs with voltage ratings exceeding 4500V are optimized normally for state-of-the-art two or three level inverters, which are usually operating at relatively higher frequencies. Therefore, in this paper, we demonstrate by simulation and experiment the feasibility of designing through “anode engineering” a wider range of HV-IGCTs with very low on-state losses approaching the 1V value, which many applications strive for today.

1. Introduction

The IGCT shown in Fig. 1 is in principle a thyristor based device concept which has since its evolution from the Gate turn-off Thyristor (GTO) in the mid 1990`s [1] established itself as the device of choice for industrial Medium Voltage Drives (MVD) and has also been used in many other systems such as wind-power conversion, STATCOMs, and interties to name a few. Due to the integration with a low inductive gate unit, this hard driven device conducts like a thyristor (i.e. low on-state losses) and turns off like a transistor (i.e. hard switching). State-of-the-art IGCTs are available as symmetric, asymmetric and reverse conducting devices with an integrated free-wheel diode having been optimized for VSI applications.

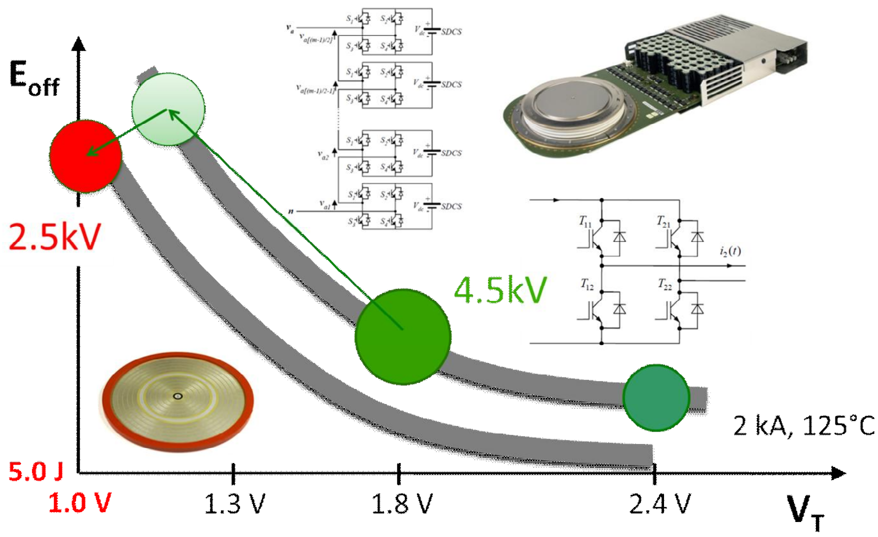

Fig. 1 Typical IGCT technology curves for 91mm components including existing high voltage 4.5kV devices and potential lower voltage classes such as 2.5kV. The arrows show the proposed trend for tailoring the IGCT towards lower on-state losses for modern topologies operating at lower switching frequencies.

Today, IGCTs have voltage ratings ranging from 4.5kV up to 6.5kV for enabling 2-level and 3-level VSI inverters. Hence, such devices are normally optimized for relatively high switching frequencies in the range of few 100Hz. With the recent trend towards employing multi-level topologies in many power electronics applications, demands are now being made for more application specific devices with a shift in focus towards lower on-state losses for operating efficiently at lower switching frequencies with higher power capabilities (see Fig. 1).

We will demonstrate in this paper that the IGCT with its optimum thyristor plasma distribution during conduction is the ideal device for bringing forth such improvements. The technology is served by tailoring the IGCT wafer towards lower on-state losses through anode engineering to achieve values approaching 1V while maintaining good overall performance. In addition, modern applications with multi-level topologies will inherently require a wider range of available voltage classes for optimising the system performance. Hence, expanding the IGCT range from its existing high voltage ratings above 4.5kV towards lower voltage ratings including 2.5kV and 3.3kV can bring forth new possibilities for the circuit topology designers.

2. Megawatt Power Semiconductors

Despite the fact that a wide range of high voltage devices with attractive electrical characteristics exist, higher power and superior overall performance remain as the main targets for satisfying the demands of new high power system designs. Fig. 2 (left) illustrates the different available silicon based power device concepts and their typical power ratings and application frequencies while Fig. 2 (right) shows the associated applications and their respective voltage and current ratings. In the megawatt range, three types of switching high voltage devices are dominant; the Phase Controlled Thyristor (PCT), the IGCT and the Insulated Gate Bipolar Transistor (IGBT). One must also not forget the power diode covering the whole power range for rectification, snubber or freewheeling purposes.

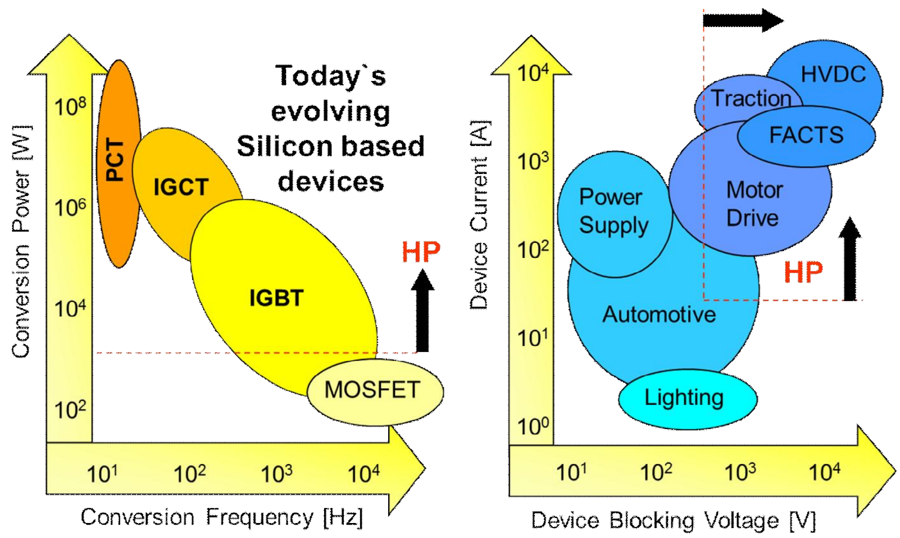

Fig. 2 Silicon based Power semiconductor devices and applications.

The dominant two high voltage components with hard switching turn-off capability, namely the IGCT and IGBT have been employed in Voltage Source Inverter VSI megawatt systems. The IGCT as for the PCT are bipolar devices operating in thyristor mode which is mainly characterized by its favourable excess carrier distribution for low on-state losses in conduction mode. On the other hand the IGBT is a MOS controlled device with a bipolar effect for achieving low on-state losses, high switching transients and short circuit mode capability. Fig. 3 shows the IGCT and IGBT basic structures and related plasma distributions. In the past two decades, the two concepts have undergone major developments, mainly aiming to reduce the overall losses and increasing the turn-off current handling capabilities.

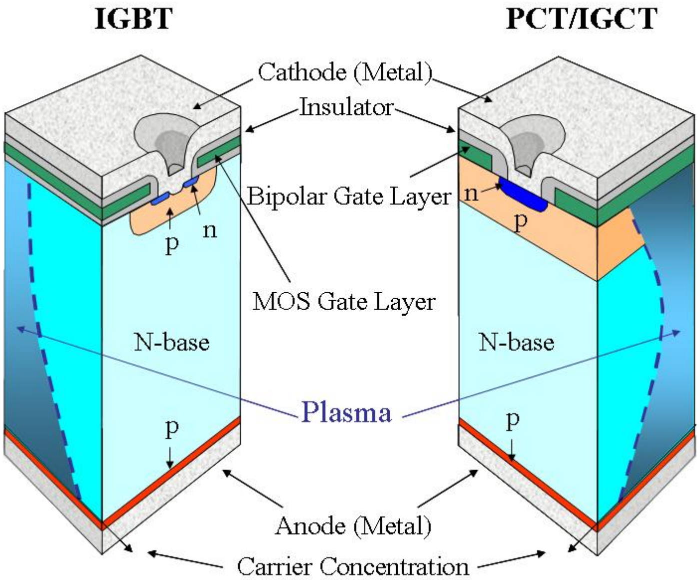

Fig. 3 IGCT and IGBT basic structures and plasma distributions.

While there are a number of differentiating elements favouring the IGBT or the IGCT for a given application with regards to the device assembly, gate controllability and fault protection techniques, the losses performance remains a major factor for the IGCT maintaining a strong position as a device of choice in many high power applications. This is the case today despite the fact that IGBTs are continuously improving their losses figures with modern cell and bulk design concepts [2]. To be able to quantify this aspect, we compare in Fig. 4 the losses performance of state-of-the-art IGBTs and asymmetric IGCTs rated at 4500V in press-pack components. Both devices have approximately 40cm^2 of active area and are plotted for the nominal turn-off switching losses E_{off} versus conduction losses at 2000A and 125°C. The typical technology curve of the 91mm 4.5kV asymmetric IGCT is generated by means of lifetime engineering and consists of an un-irradiated device (slow IGCT), a moderately irradiated standard IGCT and a strongly irradiated high frequency version (fast IGCT). The latter two devices points with higher V_T and lower Eoffs represent today`s optimized devices for 2-3 level applications. When compared to an equivalent SPT+ 4.5kV IGBT, a clear demonstration of the IGCT superior thyristor-like conduction performance is provided with close to half the conduction losses achieved for the same turn-off switching losses.

System output current performance analysis based on a 2-level inverter employing 91mm 4.5kV IGCTs show that the fast component provides the highest output currents when the system frequency exceeds 350Hz, while the slow version is optimal for operational frequencies below 125Hz. Hence, the standard version covers the intermediate range between 400Hz and 125Hz. The simulations have also shown that further optimisation of the IGCT can lead to even higher output current levels for frequencies below 85Hz (see section 4). It is the target of this investigation to show that further tailoring of the IGCT towards even lower conduction losses by anode engineering can provide the optimum losses performance points for topologies operating at lower frequencies.

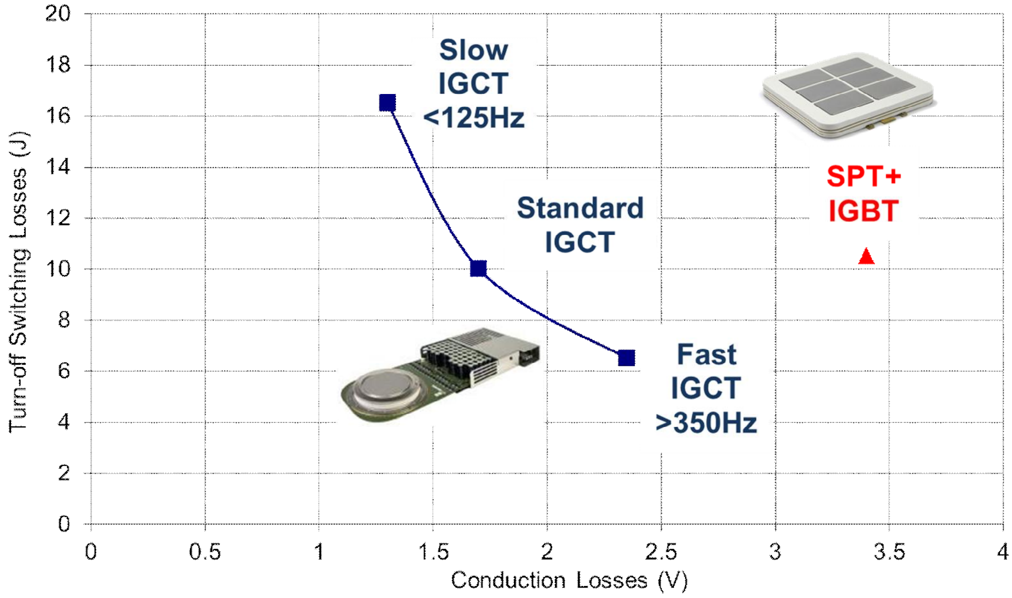

Fig. 4 The 91mm 4.5kV asymmetric IGCT technology curve compared to an equivalent 4.5kV SPT+ IGBT at 2000A, 2.8kV DC link and 125C.

3. IGCT optimisation towards 1V conduction losses

As a starting point, the investigation was focused on the 91mm 4.5kV un-irradiated slow IGCT version as depicted in Fig. 4. The device on-state losses curves at 25°C and 125°C and turn-off switching waveforms at 125°C are shown in Fig. 5.

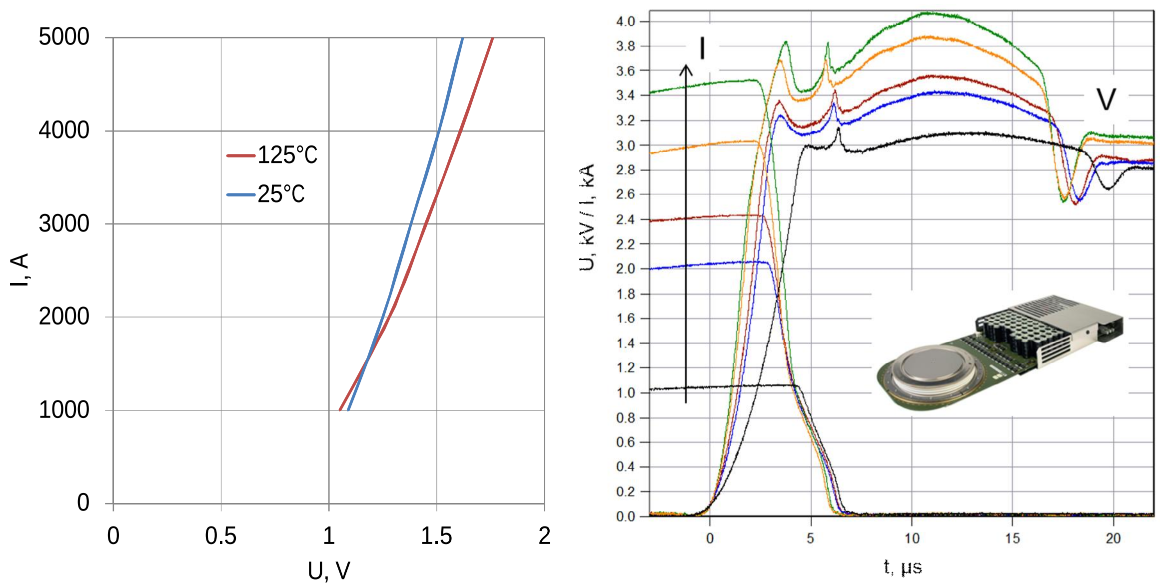

Fig. 5 Static IV curves at 25°C and 125°C f (left) and dynamic turn-off current and voltage waveforms up to 3.5kA at 2.8kV DC link and 125°C (right) for the un-irradiated 91mm 4.5kV IGCT

The on-state curves show that the IGCT provides very low losses below 1.5V up to currents of 3000A. For such a design, the impact of the high plasma levels during conduction on the device turn-off Safe-Operating-Area SOA must be considered. The IGCT turn-off switching waveforms at 125°C for currents up to 3.5kA and a DC link voltage of 2.8kV provide good evidence that the slow IGCT SOA can maintain high levels of turn-off current capability for hard switching performance [3].

Based on the 4.5kV slow IGCT, a 2D TCAD model for the asymmetric IGCT was generated and calibrated with the electrical test results presented above. As discussed previously, the IGCT is based on a “pnpn” thyristor structure as shown in Fig. 6 along with the circuit model employed for running the turn-off simulations. The device model did not include any lifetime engineering and the main target was to focus on investigating the impact of anode engineering methods.

The term “Anode Engineering” refers here to the adjustment of the p+ anode layer doping concentration towards higher levels for providing higher injection efficiency and subsequently lower conduction losses, albeit at the expense of higher switching losses.

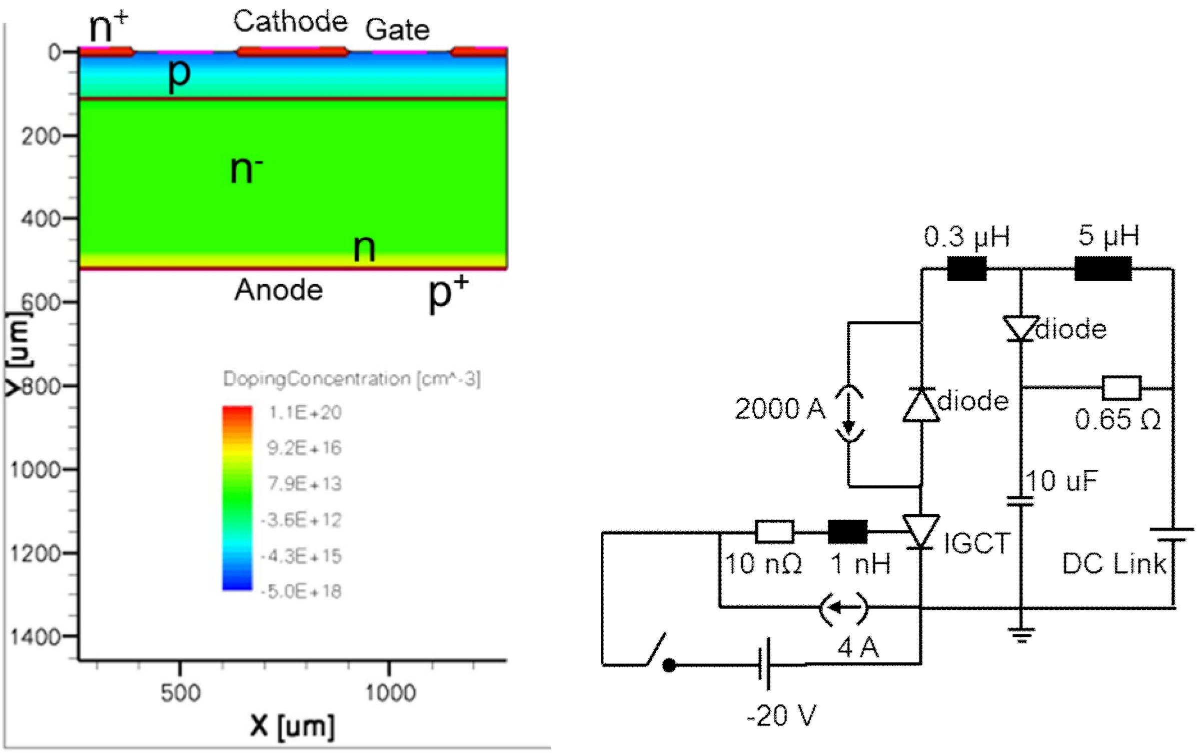

Fig. 6 2D TCAD model for the 4.5kV asymmetric IGCT (left) and turn-off circuit model (right).

Furthermore, in order to evaluate the potential losses achieved for a wide range of high voltage IGCTs with ratings ranging from 2.5kV up to 6.5kV, TCAD models were generated based on the calibrated 4.5kV model and further static and dynamic simulations were carried out. The device models n-base thicknesses and doping concentrations were varied to obtain the different voltage classes.

The full range of on-state and turn-off switching losses were obtained under nominal conditions for 91mm devices at 125° while varying the anode p-doping in three steps from structure (3) with $5x10^{17}$ /cm^2 to structure (1) at $5x10^{18}$ /cm^2 to obtain the low V_T versions. The technology curves for the different voltage classes at different currents are presented in Fig. 7. Typical on-state curves and turn-off waveforms obtained from the simulations are shown in Fig. 8 for the 91mm 2.5kV asymmetric IGCT.

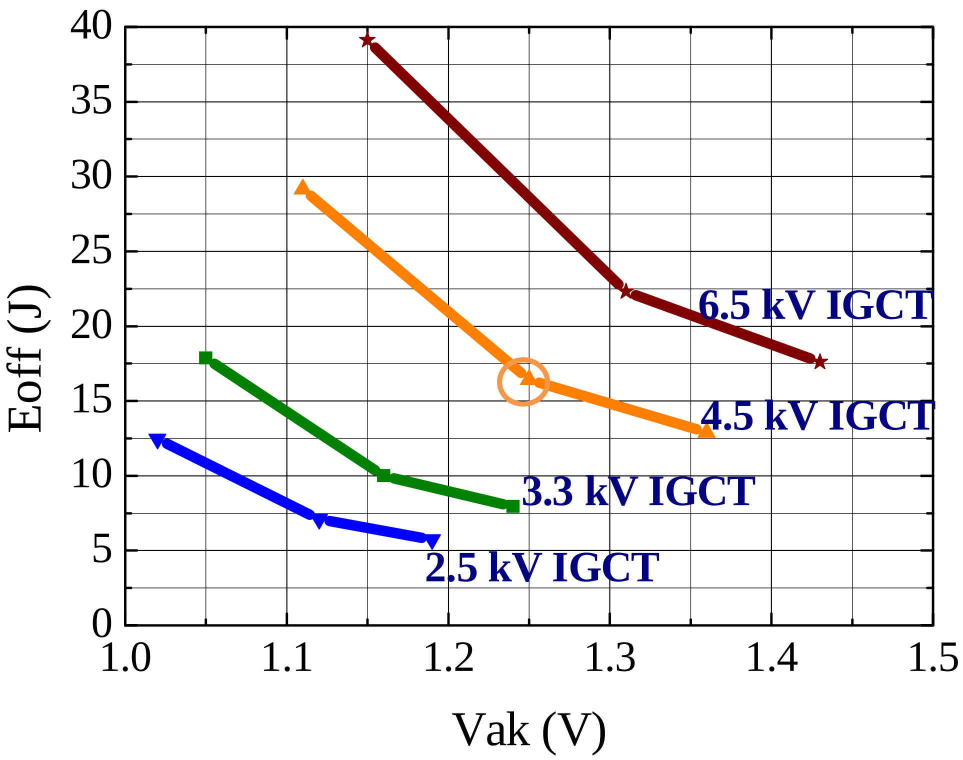

Fig. 7 Simulation technology curves at 125°C for 91mm IGCTs for (6.5kV tested at 1.5kA/3.6kV; 4.5kV tested at 2kA/2.8kV; 3.3kV tested at 2.5kA/1.8kV; 2.5kV tested at 3kA/1.3kV). The calibrated 4.5kV IGCT point for the slow version is highlighted in the circle.

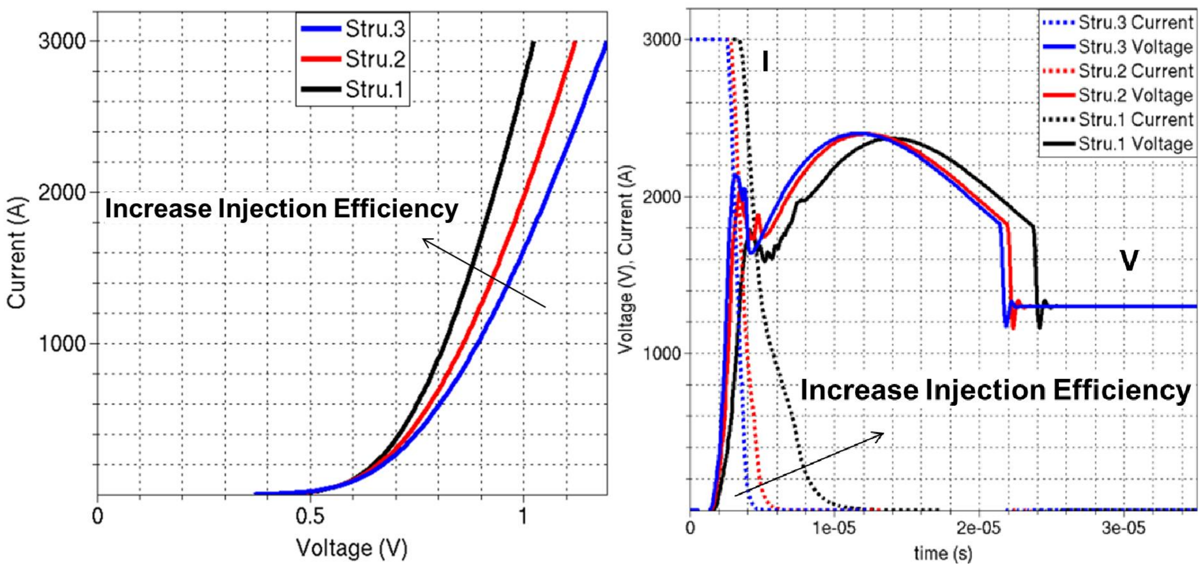

Fig. 8 Simulated Static IV curves at 125°C f (left) and dynamic turn-off current and voltage waveforms at 3kA and 1.3kV DC link and 125°C (right) 91mm 2.5kV asymmetric IGCT.

4. Technology performance curves

As seen from Fig. 7, despite the fact that the switching losses is close to doubling from structure (3) to structure (1) for most voltage classes, as mentioned previously from the output current performance analysis, structure (1) can still provide the optimum solution at operational frequencies below 85Hz for the 4.5kV voltage class. Fig. 9 shows the maximum output current capability of the 4.5kV 91mm devices (Fast, Standard and Slow) while also including the low frequency version structure (1) obtained from the TCAD simulations.

We have also included what we refer to here as the "technology cross points" for the different versions. Based on the cross points, we can determine the optimum design for a given frequency range and technology base design. The graph clearly shows that the slow and low frequency versions are well suitable for the very low end range below 100Hz when compared to the standard version. This frequency limit is normally higher for lower voltage classes due to the lower switching losses.

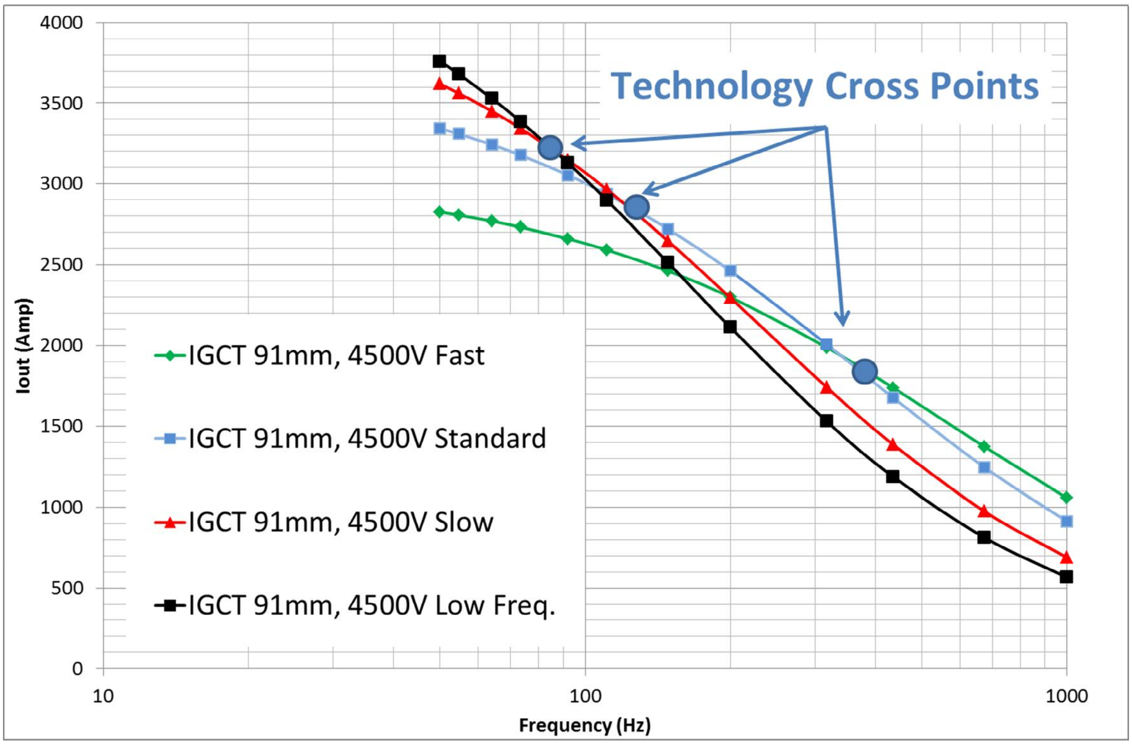

Fig. 9 Output current performance charts for the 91mm 4.5kV asymmetric IGCTs including Technology performance cross points (Inverter mode, cos phi=0.95, m=1, TA=40 °C, 125°C, 2.8kV).

5. 2.5kV symmetric IGCT prototype demonstration

To demonstrate the Safe Operating Area capabilities of an IGCT with very high anode injection efficiency, 2.5kV symmetric 91mm devices were manufactured and tested under SOA conditions. Fig. 10 shows both the on-state curves at 25°C and 125°C and the turn-off SOA current and voltage waveforms at 7000A, 1.6kV DC link and 125°C.

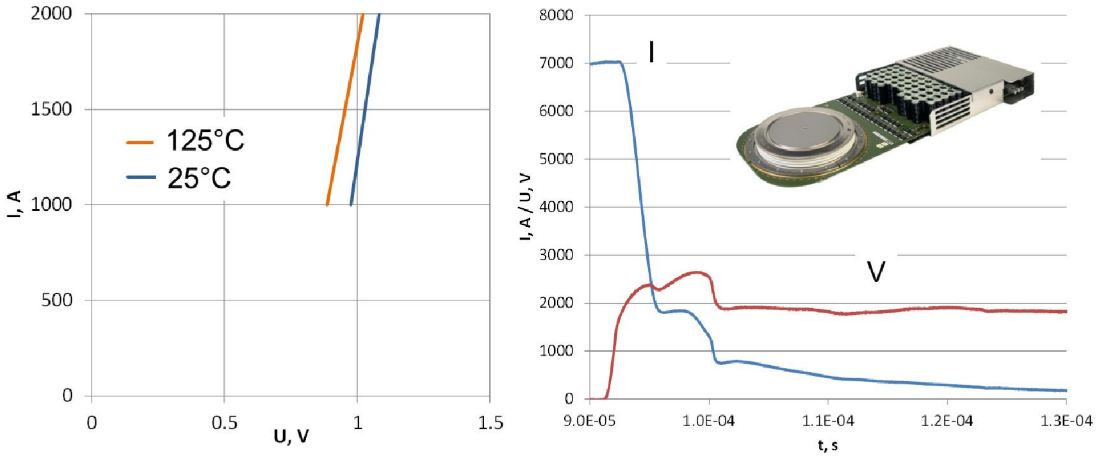

Fig. 10 Static IV curves at 25°C and 125°C f (left) and dynamic turn-off current and voltage waveforms at 7kA and 1.6kV DC link and 125°C (right) for the symmetric 91mm 2.5kV IGCT.

The on-state curves show the ultimate potential of reaching the V_T goal of 1V at reasonably high currents while at the same time, the switching waveforms demonstrate that a high level of SOA capability can be maintained under such design principles.

The next step in this investigation will be to manufacture and fully characterize a variety of anode engineered asymmetric IGCT prototypes with voltage ratings ranging from 2.5kV to 3.3kV.

6. Conclusion

In this paper, we have investigated the potential of optimising the IGCT towards very low on-state losses. The experimental and simulation results provided from this investigation will provide an overall outlook with regard to the potential of IGCTs in different voltage classes to achieve very low on-state losses approaching the typical sought after level of 1V. The advantages of the low on-state losses can be exploited by (a) providing higher output current capabilities at lower operational frequencies or by (b) targeting lower losses for higher efficiency at a given power ratings since the devices exhibit low V_T value at reasonable current levels. The main aim is to assess the suitability of such optimized IGCTs for modern and efficient power electronics applications having the main focus on lowering the conduction losses for operating at lower switching frequencies.

7. Literature

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