A NEW RANGE OF REVERSE CONDUCTING GATE-COMMUTATED THYRISTORS FOR HIGH-VOLTAGE, MEDIUM POWER APPLICATIONS

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Abstract. Until recently, the Gate Commutated Thyristor (GCT) was regarded as the ideal device for very high power applications, allowing 3/6 kA devices (with/without snubber) to be produced from 4" silicon wafers, with voltage ratings of up to 6 kV. Lower currents, it was felt were best handled by convenient modular IGBT devices. However, the thrust for reliable and efficient drives operating at dc link voltages of 2 to 10 kV, albeit at currents of only a few hundred amps, have led to the development of a complete range of reverse conducting snubberless GCTs from 200 A to 3000 A with 4.5 and 5.5 kV ratings. The ratings and characteristics of this new product range are presented.

Keywords: reverse conducting IGCT, snubberless operation

INTRODUCTION

There is a growing demand for power control at high voltage levels, namely distribution voltages of 2.3, 3.3, 4.16 and even 6.9 kV rms. This increasingly large market attracts many system manufacturers who compete aggressively for market share. Thus, power control system designs must be inexpensive but nevertheless efficient and reliable. Because power requirements are frequently modest - often only a few hundred kilowatts - the insulated gate bipolar transistor (IGBT) was the preferred active switch to fulfil these requirements. However, the IGBT suffers from a number of serious drawbacks at high dc link voltages [1]. Until recently, the only alternative for elevated voltage classes was the gate turn-off thyristor (GTO). Unfortunately, the GTO also has its shortcomings: awkward and expensive turn-off snubbers are necessary and furthermore, the maximum switching frequency is limited to a few hundred hertz because of non-uniform device heating caused by current redistribution during turn-off.

In order to be able to offer a competitive power switch for high voltage power control, ABB Semiconductors has developed a family of reverse conducting gate-commutated thyristors (GCTs), featuring the following key properties:

- wide range of applications through 8 different devices in three voltage classes; maximum rated currents of 480 A to 3100 A ($V_{dc\text{-}link}$ = 1.9 kV), 340 A to 2200 A ($V_{dc\text{-}link}$ = 2.7 kV), and 275 A to 1800 A ($V_{dc\text{-}link}$ = 3.3 kV).
- snubberless turn-off of maximum rated current at full dc link voltage.
- maximum switching frequency of more than 25 kHz, pulse burst-duration limited only by cumulative losses.
- buffer layer concept for low on-state voltage drop combined with minimal turn-off losses.
- monolithic free wheel diode for reduced power semiconductor parts-count of nearly 50% allowing higher system reliability at lower cost.
- gate unit bundled with power semiconductor *(reverse conducting Integrated GCT)* for low system development costs and reduced time-to-market.

RATINGS OF ABB SEMICONDUCTORS REVERSE CONDUCTING IGCT FAMILY

In Tables 1 through 3, the ratings of the new ABB Semiconductors' reverse conducting IGCT family are

presented. The range of 8 devices is able to cover the requirements of 2- and 3-level inverters for dc link voltages of up to 6.6 kV (2 x 3.3 kV), and turn-off currents of up to 3 kA (not concurrently). This allows the design of inverters with power ratings of 300 kW to 10 MW without series or parallel connection of elements. 2-Level inverters may be realized with as few as 7 power semiconductors. As few as 20 power semiconductors are required for a 10 MW 3-level inverter.

Fig. 1 shows a photograph of the reverse conducting IGCT family (GCTs with their bundled gate units). The gate units are controlled via fiber optic cables. Driving power is provided through a dc input. Power requirements depend strongly on inverter switching frequency, average turn-off current, and duty cycle. Therefore, the power source is not included in the gate drive. However, typical power consumptions approximately range from 10 to 30 Watts [3].

			T_j = 0 - 115°C					$V_{dc\text{-}link}$ = 3300 V				
			GCT rating					diode rating				
Part n°	V_{DRM} [V]	$V_{dc\text{-}link}$ [V]	I_{tgqm} [A]	V_T [V]	E_{off} [V]	I_{gt} [A]	$\theta jc,_{GCT}$ [K/W]	V_T [V]	di/dt [A/µs]	I_{rr} [A]	E_{off} [J]	$\theta jc,_D$ [K/W]
5SGR 03D6004	5500	3300	275	3.0	1.45	0.3	0.070	6.0	74	114	0.70	0.090
5SGX 06F6004			520	3.0	2.73	0 .6	0.04	6.0	195	268	1.62	0.053
5SGX 10H6004			908	3.0	4.77	1.0	0.025	6.5	296	433	2.63	0.042
5SGX 19L6004			1815	3.0	9.54	2.0	0.012	7.0	533	781	4.85	0.021

TABLE 1 - Preliminary ratings of 5.5 kV (3.3 kV dc link) reverse conducting GCTS. Data subject to change

			T_j = 0 - 115°C					$V_{dc\text{-}1ink}$ = 2700 V / 1900 V				
			GCT rating					diode rating				
Part n°	V_{DRM} [V]	$V_{dc\text{-}link}$ [V]	I_{tgqm} [A]	V_T [V]	E_{off} [V]	I_{gt} [A]	$\theta jc,_{GCT}$ [K/W]	V_T [V]	di/dt [A/µs]	I_{rr} [A]	E_{off} [J]	$\theta jc,_D$ [K/W]
5SGR 03D6004	4500	2700	338	3.0	1.33	0.3	0.070	6.0	113	107	0.56	0.090
		1900	482	3.7	1.33	"	"	7.5	113	116	0.42	"
5SGX 06F6004		2700	628	3.0	2.48	0 .6	0.04	6.0	294	281	1.44	0.053
		1900	894	3.7	2.48	"	"	7.5	294	304	1.10	"
5SGX 10H6004		2700	1095	3.0	4.32	1.0	0.025	6.5	448	427	2.20	0.042
		1900	1560	3.7	4.32	"	"	8.1	448	462	1.68	"
5SGX 19L6004		2700	2190	3.0	8.64	2.0	0.012	7.0	806	769	3.96	0.021
		1900	3120	3.7	8.64	"	"	8.8	806	832	3.01	"

TABLE 2 - Preliminary ratings of 4.5 kV (1.9/2.7 kV dc link) reverse conducting GCTS. Data subject to change

List of Parameters:

$V_{dc\text{-}link}$	[V]	maximum dc link voltage at 100 FIT[1]
V_{DRM}	[V]	maximum forward blocking voltage
T_j	[°C]	junction temperature

GCT Parameters:

I_{tgqm}	[A]	maximum (non-repetitive) turn-off current at $V_{dc\text{-}link}$
V_T	[V]	forward voltage drop at I_{tgqm}
E_{off}	[J]	turn-off losses at I_{tgqm} (typical: actual value depends on clamp configuration and load)
I_{gt}	[A]	GCT trigger current
$\theta_{jc,GCT}$	[K/W]	thermal resistance from GCT junction to case (assumption: only GCT dissipates heat)

Diode Parameters:

V_T	[V]	diode forward voltage drop at I_{tgq}, of GCT part.
di/dt	[A/µs]	maximum allowed current gradient at $V_{dc\text{-}link}$ during diode turn-off
I_{rr}	[A]	peak reverse recovery current of diode (at maximum allowed di/dt)
E_{off}	[J]	diode turn-off losses for maximum di/dt and $V_{dc\text{-}link}$
$\theta_{jc,D}$	[K/W]	thermal resistance from diode junction to case (assumption: only diode dissipates heat)

1. Refers to cosmic ray induced failures. *[FIT] (**F**ailures **I**n **T**ime)* = number of failures per billion hours of operation (100% duty cycle).

	Mechanical data			Blocking endurance	
Part n°	diameter of pole piece [mm]	wafer diameter [mm]	mounting force [kN]	1000 hours Tj = 115 °C	10 sec Tj = 115 °C
5SGR 03D6004	34	38	10	3300	3900
5SGX 06F6004	47	51	15	3300	3900
5SGX 10H6004	63	68	20	3300	3900
5SGX 19L6004	85	91	40	3300	3900
5SGR 04D4502	34	38	10	2700	3200
5SGX 08F4502	47	51	15	2700	3200
5SGX 14H4502	63	68	20	2700	3200
5SGX 26L4502	85	91	40	2700	3200

TABLE 3 Mechanical data and blocking endurance of reverse conducting GCTs

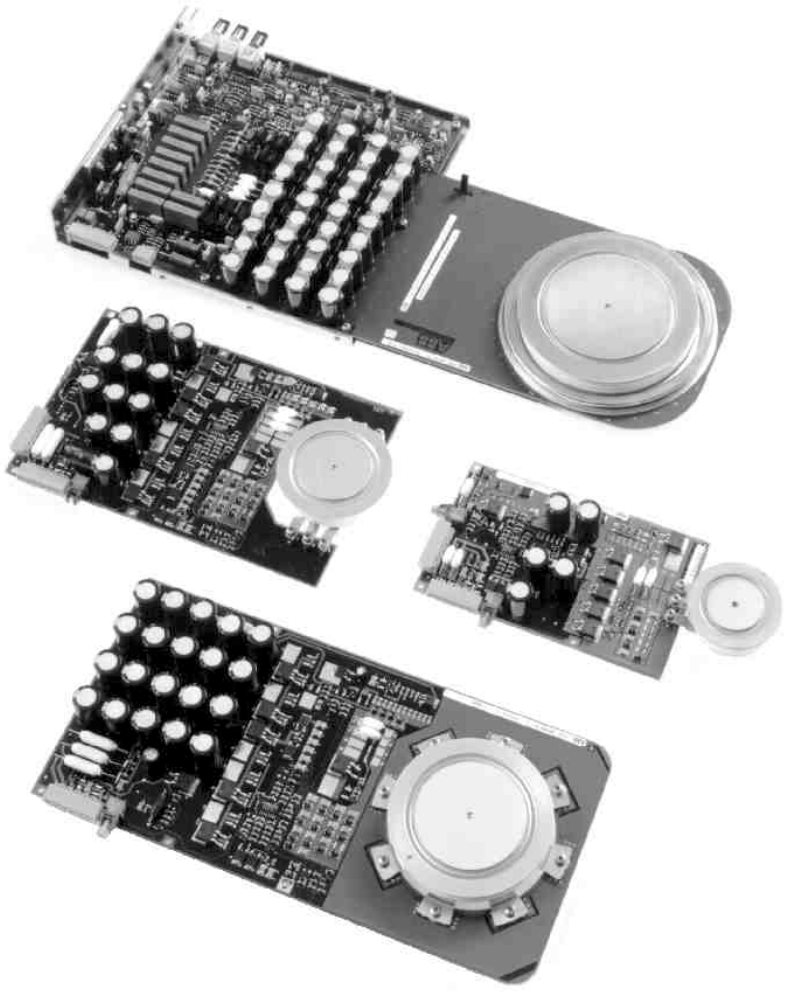

Figure 1: Photograph of reverse conducting IGCTs

GCT OPERATION PRINCIPLE

The gate commutated thyristor, until recently called *hard driven GTO thyristor* [3]) is an entirely new concept in power semiconductors. The GCT turns on with a current gate pulse and latches in forward conduction, exactly like a GTO thyristor. However, during turn-off the GCT behaves completely differently. The GCT's turn-off concept closely resembles that of the GTO cascode [2] (Fig. 2): In order to turn off a GTO cascode, the entire anode current is forced to commutate into the gate by opening a switch in series with the cathode (usually a MOSFET). Thus, the GTO is converted into a pnp transistor without a base contact. Regenerative action of the cathode emitter is prevented and the cascode GTO turns off uniformly without current crowding or filamentation with its associated hot spot formation. This theoretically makes the cascode an extremely robust switch. Maximum turn-off currents are significantly higher than ratings of conventional GTOs, and protective snubber circuitry may be omitted as it turns off at *near* unity gain.

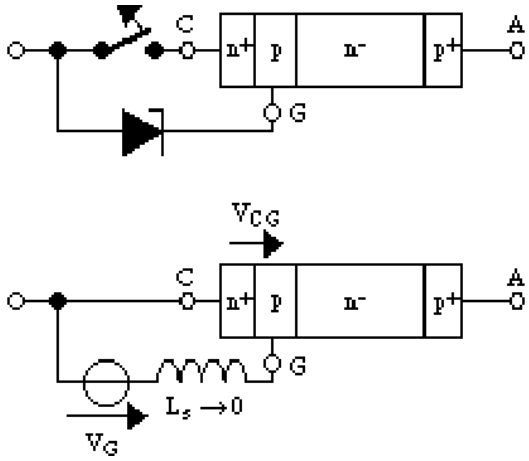

Figure 2: Turn-off principle of cascode (top) and GCT (bottom)

The GCT's improved implementation of the cascode principle works as follows: In order to turn off the GCT, the p-base — n-emitter junction is reverse biased by applying a negative voltage, thus instantly stopping injection of the cathode and turning the GCT into a pnp transistor. The concept only succeeds if the entire anode current can be commutated into the gate before a space charge region can form at the p-base — n-base junction, that is, before the device starts to build up blocking voltage. In the GCT, this occurs at *below* unity gain. Roughly, current commutation to the gate must take place within 1 s. This requirement implies tight constraints on the maximum impedance of the gate driver. For instance, in order to turn off 1000 amps with V_G = 20V, the maximum stray inductance of the gate driver can be calculated as follows:

$$V_{CG} > 0 \Rightarrow L_s < \frac{V_G}{(di/dt)} = \frac{20V}{1000A} \bullet 1\mu s = 20nH$$

Such a low gate inductance can only be achieved by a special GCT housing construction with coplanar gate-cathode conductors [3]. Moreover, the gate unit must be optimized for minimal inductance. Because the associated development effort is expensive and time consuming, ABB Semiconductors bundles all GCT products with their appropriate gate unit and offers them as IGCTs (=Integrated GCTs).

GCT AND DIODE TECHNOLOGY

Buffer Layer

Buffer layer power semiconductors (GCTs, GTOs, diodes, and IGBTs) outperform traditional elements because of their up to 30% reduced thickness for the same forward breakdown voltage. The major benefits of thin elements are lower on-state losses and significantly reduced turn-off losses.

The difference between buffer layer and conventional device design is explained with reference to Fig. 3: The traditional, so called non punch-through (NPT) concept features a thick n-base with the anode directly diffused into this n-base. In the buffer layer or punch-through (PT) design, the anode is shielded by a modest n-diffusion, and the doping of the substrate is chosen substantially lower than that of the NPT design. If forward blocking voltage is applied to the NPT-type element, the electric field extends into the n-base forming a triangular field distribution. Breakdown occurs if the field peak at the junction reaches the avalanche limit. In a well designed element, this happens before the field reaches the anode diffusion (therefore *non* punch-through). In the PT concept, the electric field is stopped by the n-buffer, and thus, a trapezoidal field distribution results. Because the field gradient in the PT design is much smaller with respect to the NPT-type element (lower n-base doping!), the electric field at the junction will, nevertheless, typically be the same for both approaches. Thus, the PT element is able to block the same voltage as the NPT element, but at a significantly lower thickness.

Transparent Anode Emitter

Instead of having conventional shorted anodes, all ABB Semiconductors' GCTs are equipped with *transparent anode emitters*. A transparent anode is a pn-junction with current dependent emitter efficiency [5].

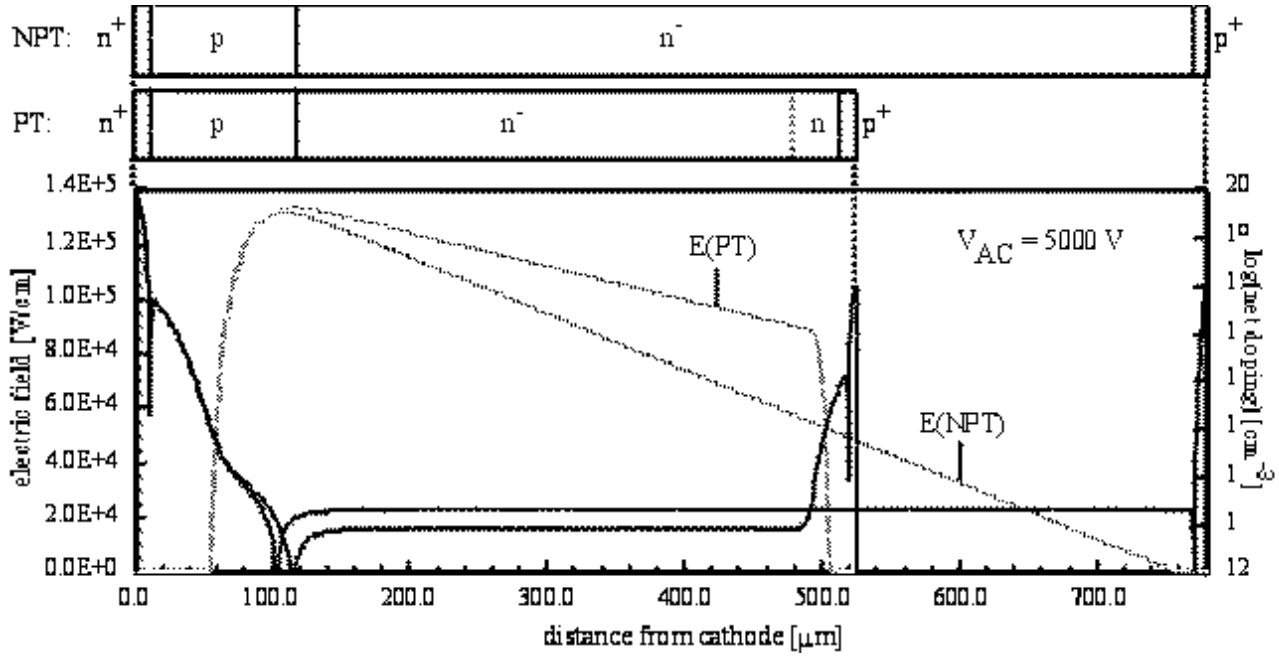

Figure 3: Comparison of electric field distributions at $V_{anode\text{-}cathode}$ = 5000 V of *non punch-through* (NPT) element and *punch-through* (PT) device.

At low current, the emitter efficiency is very high. Thus, trigger current and back porch current requirements of transparent emitter GTOs and GTCs are very small. On the other hand, the transparent emitter is engineered for low injection efficiency at high current density (thyristor latched). Hence, during turn-off, electrons can be extracted through the transparent anode as effectively as through conventional anode shorts.

Diode Co-Integration and Separation Region

In the past, the advantages of monolithic non punch-through GTO/diode combinations were always offset by the fact that the NPT GTO needed to be thicker than its corresponding free wheel diode (the diode is a PT element by nature!). Thus, reverse conducting GTOs suffered from excessive diode losses. The buffer layer concept (see previous section) overcomes this thickness trade-off. The minimum thickness of a PT GCT and of a diode are essentially the same, which in turn makes monolithic GCT/free wheel diode combinations very attractive. Fig. 4 shows a schematic cross-section through a reverse conducting GCT. Special care must be taken at the boundary between both parts. If diode and GCT share a common blocking junction (GCT p-base and diode anode joined), there will be an undesirable resistive path between GCT-gate and diode-anode. This problem is overcome by complete separation of the two p-diffusions. Due to the resulting pnp structure, one pn-junction will always be reverse biased, and thus, prevent significant current flow between GCT gate and diode anode.

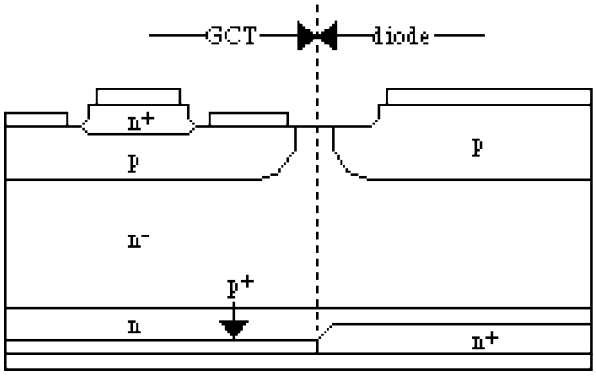

Figure 4: Schematic of separation region between GCT and diode part

Typical Inverter Design for Snubberless Operation

Fig. 5 shows one possible design for a snubberless inverter half bridge test circuit with reverse conducting IGCTs [4]. The inductance L_i limits the di_{AC}/dt upon GCT turn-on to $V_{dc\text{-}link}/L_i$. This limitation is absolutely essential for the protection of the free wheel diode during turn-off: Because the diode has no dv/dt limiting snubber, the power density during diode turn-off must be held within safe limits by limiting the reverse recovery current peak I_{rr} (which strongly depends on the di/dt).

In order to limit the voltage overshoot across the GCT during turn-off, the inductance L_i must be appropriately clamped. This may be done using diode D_c and resistor R_c. The additional capacitance C_c is optional but very useful because it efficiently clamps additional stray inductances L_{s2} in the circuit and also reduces the overall losses of the di/dt limiter.

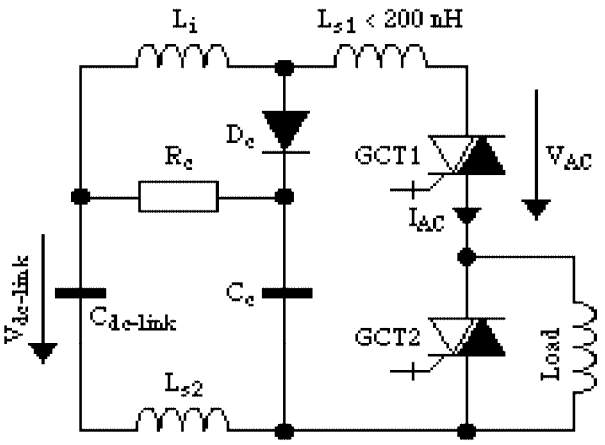

Figure 5: Example of snubberless half-bridge test circuit with two reverse conducting GCTs.

RESULTS

GCT Turn-On and Turn-Off

Fig. 6 shows typical GCT switching waveforms produced by the previously discussed configuration (Fig. 5). Prior to GCT turn-on, a current of 400 A was built up in the free wheel loop. The current peak immediately following GCT turn-on is reverse recovery of the free wheel diode. The lower part of Fig. 6 shows a magnification of the turn-off. Because there is no snubber, the voltage at the GCT rises with a dv/dt of up to several kV/ms. If the load is purely inductive (as in the given example), the GCT current remains unchanged until the voltage reaches $V_{dc\text{-}link}$. Exactly at this moment, the current commutates to the clamp. The voltage spike across the GCT is caused by stray inductances (L_{s1} in Fig. 5 and further stray inductances in the clamp). Because of the buffer layer technology, the tail current period of the GCT is very short. Roughly 5-6 s after initiating turn-off, the GCT is completely off.

Diode Turn-Off

Fig. 7 shows the snubberless turn-off of the monolithic free wheel diode with the maximum allowed di/dt. The load in this example is purely inductive and L_{load} much greater than L_i. These are the hardest possible conditions for the diode, because it experiences the full dc-link voltage at the reverse recovery peak current. Nevertheless, the diode recovers softly and causes virtually no oscillations.

The maximum power density during diode turn-off strongly depends on the reverse recovery current peak (I_{rr}). If the power density exceeds a certain limit, the diode will be destroyed by dynamic avalanche breakdown. Thus, I_{rr} must be controlled carefully.

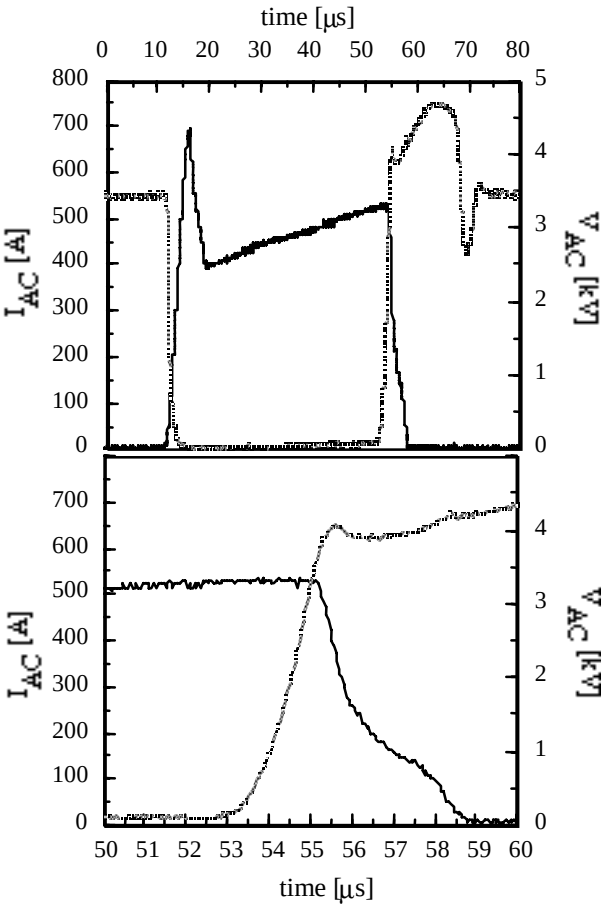

Figure 6: Snubberless operation of a ∅51 mm/5.5 kV reverse conducting GCT (part n° 5SGX 06F6004). Conditions: $V_{dc\text{-}link}$ = 3.3 kV, T_j = 115 °C, L_i = 17 µH. I_{load} (prior to GCT turn-on) = 400 A.

Major design parameters for I_{rr} are (a) carrier lifetime at the diode junction, (b) di/dt at diode turn-off, and (c) diode forward current immediately prior to turn-off. Using local lifetime control, I_{rr} of the GCT diodes was optimized for current commutation from free wheel diode to GCT in about 4 s (3.3 kV dc-link), 5 s (2.7 kV dc-link), and 6 s (1.9 kV dc-link), respectively.

High Frequency Pulse Bursts

One of the most impressive capabilities of the GCT is its ability to handle high frequency turn-on/turn-off pulse bursts. Traditional GTO thyristors require a fairly long time between two consecutive turn-off operations. During turn-off, current redistribution across the GTO and current crowding under its emitters lead to a non-uniform temperature distribution (which additionally provokes non-uniform turn-on). This situation can rapidly lead to hot spots and thermal runaway. Thus, the minimum time between consecutive GTO switching operations is basically determined by the time needed to return to *uniform* junction temperature. The GCT, however, overcomes this limitation because of its extremely uniform switching behaviour.

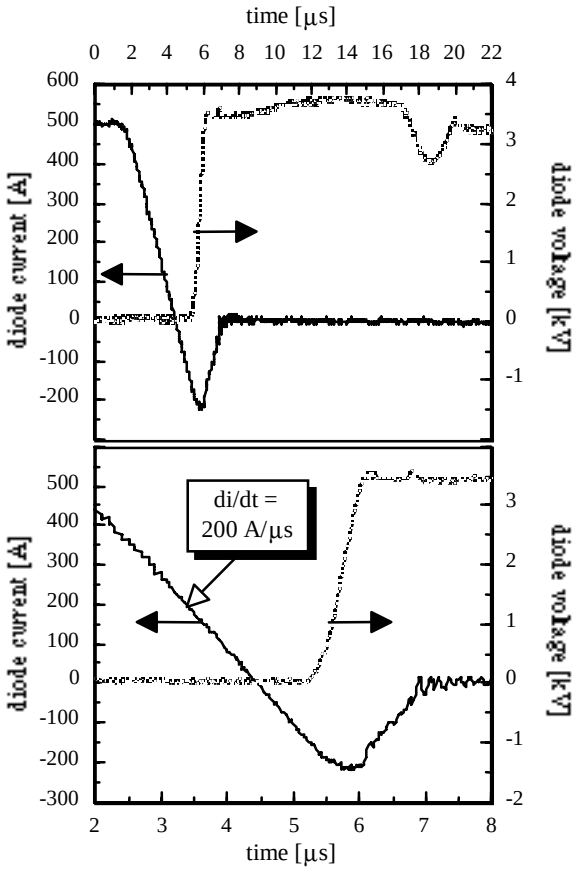

Figure 7: Snubberless turn-off of monolithic free-wheel diode (part n° 5SGX 06F6004). Conditions: V_{dc} = 3.3 kV, T_j = 115 °C, L_i = 17 H. I_o (prior to diode turn-off) = 520 A

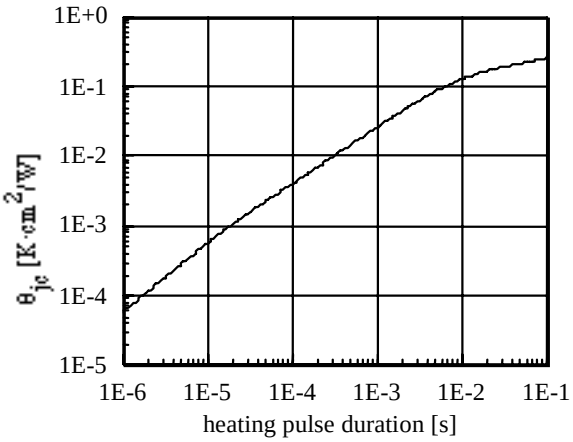

Figure 8: GCT junction-to-case thermal resistance for short heating pulses

The heat that is generated during turn-off is evenly distributed across the entire device, which means that the GCT has no “thermal memory” other than its virtual junction temperature. Therefore, the only parameter limiting the GCT switching frequency is its “thermal budget”.

The thermal resistance of ABB Semiconductors’ GCTs as a function of time (for a constant power density) is shown in Fig. 8. Because of the thermal capacitances, $_{jc}$ is much lower for short heating pulse durations than for steady state heating. Therefore, short pulse bursts can be executed without excessive temperature excursions. Fig. 9 shows a 10-pulse, 25 kHz sequence with a 25% duty cycle (10 s on / 30 s off).

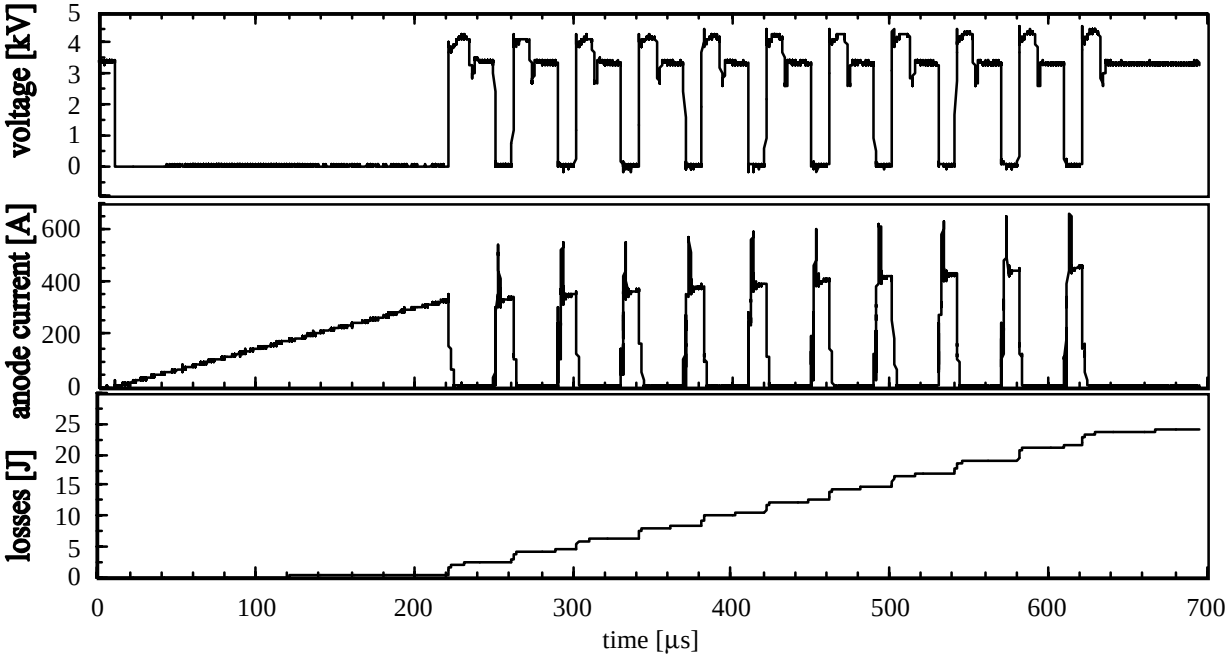

Figure 9: 25 kHz, 10-pulse test with 5SGX 06F6004. Conditions: $V_{dc\text{-}link}$ = 3.3 kV, $T_{j\ (t\ =\ 0)}$ = 80 °C, L_i = 17 mH, Load = 2 mH/50 m , t_{on} = 10 s, t_{off} = 30 s.

At its last pulse, the GCT switches off 95% I_{tgqm} (500 A vs I_{tgqm} = 520 A, see Table 1)! The lowest part of Fig. 9 shows the cumulative losses during the pulse sequence. Prior to the burst, the junction is at 80 _C. After its completion, T_j reaches approximately 180 _C! Nevertheless, the GCT can survive this torture because the hot junction is at a safe distance from the temperature sensitive junction termination. It must, however, be stressed that Fig. 8 only serves to gain a rough idea of the junction temperature after high frequency pulse patterns. Careful temperature distribution analysis by means of finite element methods should be carried out to evaluate critical pulse patterns.

The benefits of high frequency GCT operation are manifold but probably the most important is the improved ability to control complex inverter - load interactions and fault conditions.

CONCLUSIONS

The GCT is a superior power switch for high voltage and high current. Its extremely robust turn-off behaviour allows snubberless inverter design. The ability of the GCT to operate at tens of kHz (for short periods) allows it to handle even complex control transients. Thus, it is foreseeable that the GCT will soon inherit from GTOs the crown jewels in the realm of high power. Through the consequent application of new technologies, namely buffer layer and transparent emitter design, ABB Semiconductors is able to offer a complete family of reverse conducting IGCTs with near optimal GCT and diode performance. 2-Level inverters for several MW may thus be designed with as little as 7 power semiconductors. ABB offers all of its GCT products alone or with bundled gate units (IGCTs) in order to reduce equipment development costs and time-to-market.

Acknowledgements

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References

[1] Carroll, E., Klaka, S., Linder, S.: “Integrated Gate-Commutated Thyristors: A New Approach to High Power Electronics”, Press Conference, IEMDC, Milwaukee, May 20, 1997

[2] Wirth, F.: “The Gate Turn-Off Thyristor in the Cascode Configuration”, IEEE IAS Conf. Proc. 1983, pp. 788 - 793

[3] Grüning, H., Ødegård, B., Rees, J., Weber, A., Carroll, E., Eicher, S.: “High-Power Hard-Driven GTO Module for 4.5 kV / 3 kA Snubberless Operation”, PCIM’96 Conf. Proc. (ISBN 3-928643-12-6), 1996, pp. 169 - 183

[4] Grüning, H., Rees, J.: “Stromrichterschaltungsanordnung”, German Patent Application D19543702.0 (Patent Pending).

[5] Eicher, S., 1996, “The Transparent Anode GTO (TGTO): A New Low-Loss Power Switch”, Series in Microelectronics - Volume 58, Hartung-Gorre, Konstanz. ISBN 3-89649-073-7