Application Specific IGCTs

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Abstract *IGCTs have established themselves as the power semiconductor of choice at medium voltage levels within the last few years because of their low conduction and switching losses. The trade-off between these losses can be adjusted by various life-time control techniques and the growing demand for these devices is driving the need for standard types to cover such applications as Static Circuit Breakers (low on-state) and Medium Voltage Drives (low switching losses). The additional demands of Traction (low operating temperatures) and Current Source Inverters (symmetric blocking) would normally result in conflicting demands on the semiconductor. This paper will outline how a range of power devices can meet these needs with a limited number of wafers and gate units. Some of the key differences between IGCTs and IGBTs will be explained and the outlook for device improvements will be discussed.*

I. PRINCIPAL OF OPERATION

The semiconductor part of the IGCT (**Integrated Gate-Commutated Thyristor**) [1] is a 4 layer device similar to a GTO (Gate Turn-off Thyristor). It is mounted („integrated“) into its gate drive unit which results in an extremely low inductance coupling between semiconductor and gate-unit. This low inductance connection allows the thyristor or „GCT“ to be turned off with unity gain via a low voltage source (20 V – see Fig. 1b) [2]. The vertical structure of the GCT, though derived from the GTO, has benefitted from high voltage IGBT (Insulated Gate Bipolar Transistor) developments and incorporates such loss-reduction techniques as the Buffer Layer [3] and the Transparent Emitter. These techniques lead to thinner wafer designs than was possible for GTOs which further allows the monolithic integration of an anti-parallel diode onto the same wafer for reverse conduction [4] which was not optimally feasible with GTOs. The result is a switch which behaves like an IGBT at turn-off (open-base pnp transistor) and generates the same turn-off losses. In conduction however, the IGCT is a thyristor (see Fig. 1a) and as such it generates substantially lower losses than an IGBT. This is due to the fact that a thyristor operates at much higher charge density than a transistor due to charge injection from its two emitters (pnp- und npn-transistors).

The design of the IGCT gate-unit allows a short but high value of turn-on gate current (typically 5 times higher than in GTO practice) which drives on the GCT as an npn transistor [5] (short delay time, monotonic voltage collapse, negligible losses). Thus the IGCT is a thyristor in conduction, a pnp transistor at turn-off and during blocking and an npn transistor at turn-on. Like the transistor, the IGCT requires no dv/dt limitation at turn-off but *unlike* the transistor, it is not possible to control turn-on nor turn-off speed.

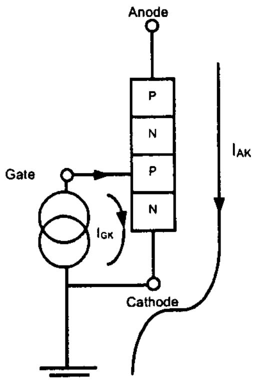

Fig. 1a **Conducting** (Thyristor)

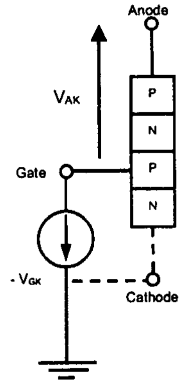

Fig. 1b **Blocking** (Transistor)

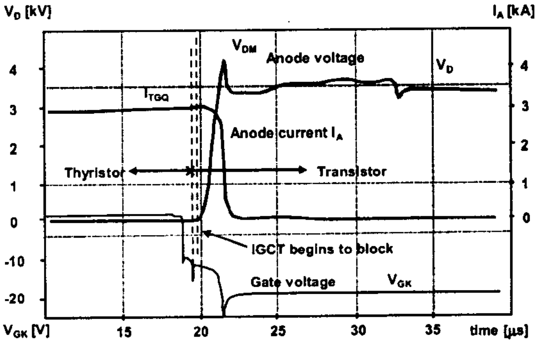

Fig. 2 IGCT Turn-off. The IGCT turns off like a transistor

Switch characteristic at 3 kA, 3 kV, 125°C	**IGBT** (3 x 1500 A Module)	**IGCT** (1 x 4000 A presspack)
On-state voltage	*3.7 V*	*2.2 V*
E_{OFF}	*15 Ws*	*17 Ws*
E_{ON}	*22 Ws*	*1.2 Ws*
GU power consumption @ 1kA/500 Hz pwm	*15 W*	*75 W*
Shoot-though	self limiting	external limitation (choke)
dv/dt-snubber	no	no
di/dt-snubber	no	yes
Semiconductor	discrete chips	monolithic wafer
Contact technology	solder/bondwire	pressure contact

Table 1 Comparison of 4.5 kV IGBTs and IGCTs in VSI applications (*measured values*)

Table 1 compares the salient characteristics of IGBTs and IGCTs in voltage source inverters (VSIs) and Figs. 3a and 3b show the corresponding basic topologies.

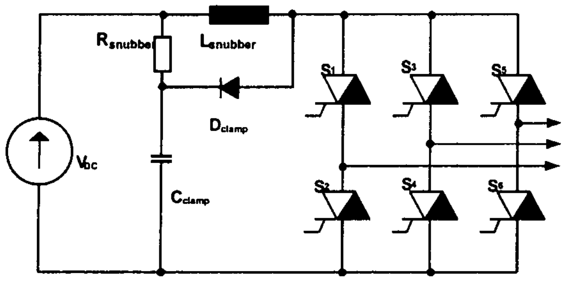

Fig. 3a Typical voltage source IGCT inverter
$S_1 \ldots S_6$: reverse conducting IGCTs

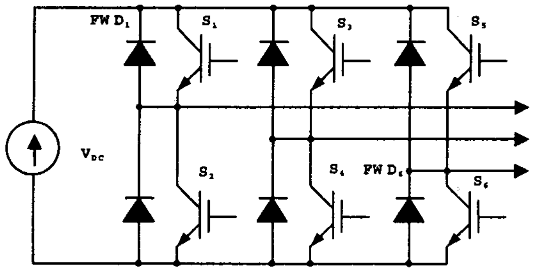

Fig. 3b Typical voltage source IGBT inverter
$S_1 \ldots S_6$: IGBTs,
$FWD_1 \ldots FWD_6$: Freewheel diodes

II ON, OFF AND CONDUCTION LOSSES

Table 1 shows that total losses are lower for the IGCT than for the IGBT. Although the turn-off losses are similar ('open-base' transistors), the total losses differ by a factor of two and the turn-on losses by a factor of twenty. This difference is due to the fact that the IGCT circuit requires an external di/dt limitation in the form of a choke as shown in Fig.4. This choke stores energy during turn-on, subsequently dissipating *most* of it in resistance $R_{Snubber}$. By contrast, the IGBT uses gate-control to adjust the turn-on di/dt thus dissipating in itself the energy that would otherwise have been stored in the choke of Fig. 4. It should be noted that this stored energy is subsequntly dissipated to only 70 – 80% in resistance $R_{snubber}$, the rest goes to supplying some of the IGCT and FWD turn-off losses which would otherwise have had to come from the DC link. Thus, contrary to popular belief, the di/dt limiting choke actually *increases* system efficiency.

Fig. 4 shows the simplified phase-leg which is relevant for the waveforms of Fig. 5. The di/dt control is required to limit the reverse-recovery current peak I_{rr} of the bipolar FWD at turn-on of the IGCT.

The available diode technologies for IGBTs and IGCTs are the same and thus the maximum allowable turn-on di/dt is also the same for both, only the means of achieving it is different: The allowed di/dt is achieved by gate control in the IGBT and by external means (a choke) with the IGCT. Fig. 5 shows the stylised turn-on waveforms for both IGCTs and IGBTs in their respective circuits of Figs. 3a and 3b respectively.

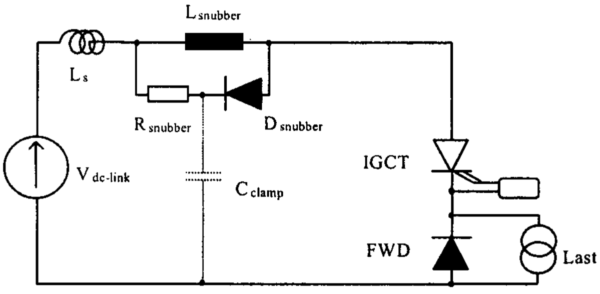

Fig. 4 Combined voltage clamp and di/dt snubber [10]

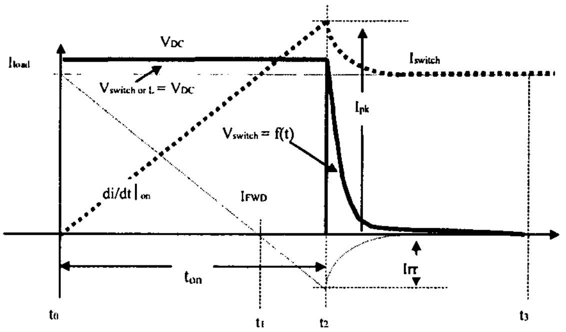

Fig. 5 Stylised turn-on waveforms of IGCTs and IGBTs in their respective circuits (Figs. 3a and 3b)

The $di/dt|_{on}$ in Fig. 5 is equal to the allowable rate-of-fall of current in the freewheel diode (FWD); I_{load} is the load current. During time t_{on} (= t_2-t_0), DC link voltage(V_{DC}) is sustained by the IGBT (gate controlled, Fig. 3b) or by the choke ($L_{snubber}$, Figs. 3a and 4). Since the FWD has a given recovery time (hence the need for di/dt-limitation), the load is short-circuited until time t_2. The circuit-specific turn-on loss (i.e. resulting from diode „slowness“) is thus given by:

$$E_{on}(circuit) = (t_2 - t_0)\cdot V_{DC}\cdot(I_{load} + I_{rr})/2 \qquad (1)$$

whilst the device specific turn-on loss is given by:

$$E_{on}(device) \approx I_{load}\cdot V_0 \cdot \int_{t_2}^{t_3} V_{device}(t)\cdot dt \qquad (2)$$

The term $V_{device}(t)$ depends on device characteristics. As such, the time constant of the falling voltage (Fig. 5) across the switch is a function, in the case of an IGBT, of the device's short-circuit withstand capability which in turn depends on the DC link voltage V_{DC}.

In E^{qn} (2), $V_0 = V_{DC}$ for the IGBT, but $V_0 \approx 0$ for the IGCT, since, in this case, link voltage is sustained by $L_{snubber}$ and not by the device. Both equations are valid for IGBTs without a di/dt snubber as well as for IGCTs with the di/dt snubber (see Table 2).

	IGBTs without di/dt-snubber (Fig. 3b)	**IGCTs with di/dt-snubber (Fig. 3a)**
E_{on}*(circuit)* per E^{qn} (1)	dissipated in device	about 75% dissipated in $\mathbf{R_{snubber}}$; the rest supplies part of the turn-off losses (see Fig. 5)
E_{on}*(device)* per E^{qn} (2)	dissipated in device (**high losses for high** SCSOA devices)	dissipated in device (but negligible)

Table 2 Comparison of turn-on losses for IGBTs without di/dt-snubber with those of IGCTs with di/dt snubber

For a 3 kA application (three parallel modules) with an allowable di/dt of 750 A/µs per module switching against a 3 kV DC link, we obtain per E^{qn} (1) losses of about 11Ws per pulse (dependant on I_{rr} of FWD), or 5.5kW at 500Hz. Per E^{qn} (2) (and also per measurement) these losses double (+ 5.5kW), dependant on the SCSOA design of the IGBT (Short Circuit Safe Operating Area). The turn-off losses generate a further 7.5kW. Adding the conduction losses (for a duty cycle of $\alpha = 0.3$) we obtain another 2kW for the IGCT und 3.3kW for the IGBT. Thus, for this example, twice the silicon would be needed for an IGBT design (Fig. 3b) as for an IGCT design (Fig. 3a), principally because of the circuit-specific losses in the switch without external di/dt control.

The maximum steady-state switching frequencies as well as the burst-mode peak frequencies which can be achieved with IGBTs or IGCTs are dependant on the total losses and the thermal resistance of the semiconductors. The lower the conduction losses, the higher the switching losses which may be generated for a given cooling. 6 kV IGCTs have been shown to operate up to 25 kHz burst mode (10 pulse) at rated current and voltage, precisely because of their low losses.

III. APPLICATIONS

Fig. 6a shows a 30MW Energy Management System, built from standard IGCT phase-legs (see Fig. 6b).

Today's commissioned IGCT equipments range from 0.3 to 5 MW general purpose MVDs [6] through 5 MW DVRs, DUPSs and Solid State Breakers [6,7], 22 MVA DVRs, 15 MW Metals Drives [8], 25 MW SMES [9], 15 MW BESS (Battery Energy Storage Systems) and up to 100 MW interties [10]. This wide power range has been covered by IGCTs in just four housing types with no paralleling of semiconductors. It is estimated that over 2 GW of IGCT equipment has been commissioned since 1995 with at least a further 1 GW pending at the time of writing.

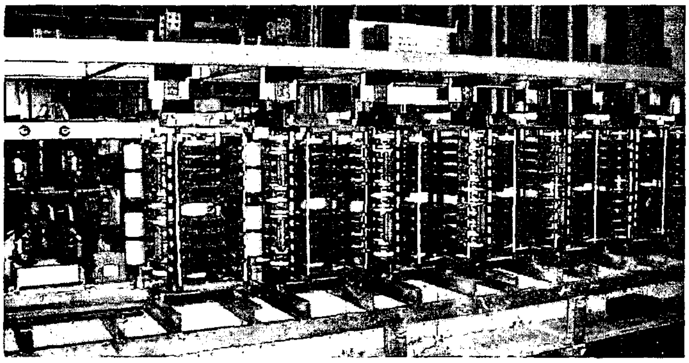

Fig. 6a 30 MW IGCT *Power Management* System with 99.6% efficiency per inverter

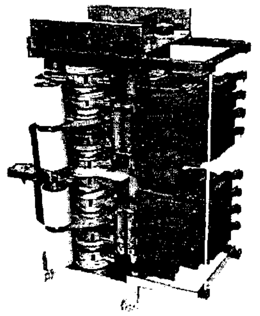

Fig. 6b Phase-leg with 27 MW/m^3 power density

IV. IGCT PRODUCT RANGE

A Present Range of IGCTs

The present IGCT product range consists of reverse blocking, asymmetric and reverse conducting devices of 4.5 und 6kV rating (see Table 3).

		Reverse Conducting				Reverse Blocking		Asym.
V_{DRM} ↓	Si Ø →	38 mm	51 mm	68 mm	91 mm	51 mm	68 mm	91 mm
4500 V	I_{TGQ} →	340 A	640 A	1100 A	2250 A	/	/	4000 A
6000 V	I_{TGQ} →	275 A	520 A	910 A	1820 A	800 A	1400 A	3000 A

Table 3 IGCT Product Overview

B A New Generation of Application- Specific IGCTs

The first IGCT, launched in 1997 (4kA, 4.5kV asymmetric type) has found its way into many different applications. Three new variants of the original version are now available making the devices „application specific“ in the sense of being optimised for a range of different applications (see Table 4 and Fig. 7). By using various lifetime control techniques, three different trade-offs of conduction vs turn-off loss are now available as standard allowing application-optimised device selection. Because of the expanded range of applications, the gate unit (an integral part of the component by definition) has also been adapted to various needs such as those of voltage and current source inverters (VSI and CSIs), series and non-series connection, low and high frequency applications, wide temperature ranges (-40 to +125°C) and vibration, as encountered in Traction environments. The standardisation of a single gate-unit to cover all the aforementionned needs is only possible because the IGCT, in contrast to the IGBT, does not actively control di/dt nor dv/dt. Apart from the gate-unit, the housings are also standard up to device ratings of 6.5 kV which leads to simplifications in manufacturing. Together with its monolithic wafer, these features lead to reliability and cost-effectiveness in Power Electronics.

Type	**Low on-state losses (Type 12)**	**Low total losses (Type 10)**	**Low switching losses (Type 11)**
Part N°	5SHY 35L4512	5SHY 35L4510	5SHY 35L4511
Junction temp. range	-40°C - 125°C	-40°C - 125°C	10°C - 125°C
V_{TM} @ 4 kA, 125°C	2V	2.7 V	3.5 V
E_{OFF} @ 4 kA, 2.8 kV, 125°C	37 Ws	22 Ws	17 Ws
Typical application	AC/DC breakers	Traction, Energy Management	high frequency MVDs

Table 4 Overview of the three new versions or the 4.5 kV asymmetric IGCTs and their typical applications

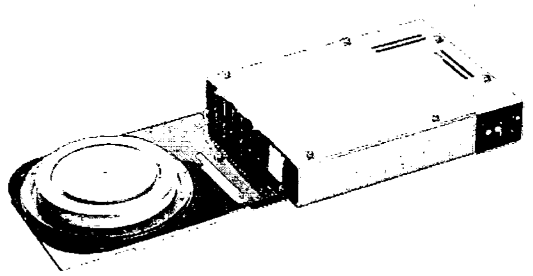

Fig. 7

New IGCT types 5SHY 35L4510/11/12 showing versatile gate-unit for VSI and CSI applications down to -40°C (5SHY 35L4510) and PWM frequencies of 1000 Hz (5SHY 35L4511 & 12).

All three types have a single AC power supply, fibre-optic gate-status feedback, visible LED status indication, are suitable for series connection and meet IEC 61373 vibration requirements.

V. OUTLOOK

IGCTs currently operate at power densities of 250 kW/cm^2 but twice this SOA has been demonstrated [11] and it is expected that devices with such improved ratings will go into production in the coming years.

Thanks to inorganic passivation, snubberless T_J ratings have risen from 115°C to 125° and will rise to 140°C in the next two years, at least for 4.5 kV devices. Surge ratings will double in the same period allowing the clamp inductances to be reduced by a factor of up to four. This will in turn raise the demands for diode di/dt capability. Snubberless diodes today operate at about 150 kW/cm^2 but SOAs of 1 MW/cm^2 have been demonstrated [12].

Requests for IGCTs of higher and lower voltage and current ratings surface regularly. Lower current and voltage ratings are purely a commercial issue and will depend on market potentials and the "pros and cons with respect to IGBTs. Larger currents have already been realised (up to 6 kA [13]) and will become more common in Metals Drives and Power Management applications. Of particular interest is the higher voltage IGCT (e.g. 10 kV). This device is under serious consideration because of the numerous MV applications at the 6.9 kV level and the need to minimise component count. Fig. 8 shows the simulated turn-off waveform of a 10 kV/2 kA device. Feasibility has been verified [14] but the acceptability of trading-off series-connection (2 x 5.5 kV) against either current or frequency de-rating has yet to be established. Additionally, first measurements of dual-gate IGCT technology [15], indicate that the tail losses (see Fig. 9) can be completely eliminated and ultra-low on-state voltages can be achieved (2.1V @ 4000A @ 125°C). The dual-gate technology would exploit its full potential, most probably, combined with high voltage devices (e.g. 10kV).

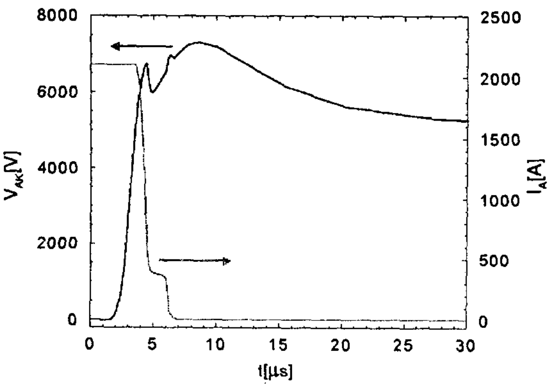

Fig.8 Simulation of 91 mm/10 kV IGCT turn-off
E_{OFF} = 20 Ws at I_{TGQ} = 2.1 kA, V_{DC} = 5.13 kV, T_j = 117°C
V_{TM} = 5.3 V at 2100 A, T_j = 117°C

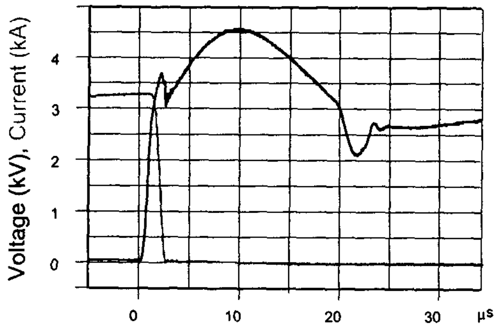

Fig. 9 Measurements of 4.5kV, 3300A dual-gate IGCT turn-off
E_{OFF} = 13.5 Ws at I_{TGQ} = 3.3 kA, V_{DC} = 2.8 kV, T_j = 85°C
V_{TM} = 2.1 V @ 4 kA/125°C

VI. CONCLUSIONS

After five years of service and after only four years of market introduction, the IGCT has established itself as a polyvalent power switch for Energy Management (Power Quality), Traction and Industrial Drives in both VSI and CSI topologies and is finding new applications in Power Generation and Industrial Processes such as high current rectifiers and induction furnaces.

The need for both component and *platform* standardisation is met by using standard wafers tailored only by lifetime engineering technologies („back-end" processes). Together with standard gate-units and housings, IGCTs allow *flexibility* and *standardisation* for both equipment and semiconductor manufacturers. Both these aspects are essential requirements for the realisation of reliable and cost-effective designs in high power electronics. With only four standard housings/gate-units and ease of series connection, IGCT equipments today cover a power range from 0.3 to 300 MW.

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