IGCTs for Induction Heating

A. Weber, E. Carroll, M Frecker

ABB Switzerland Ltd, Semiconductors, Switzerland

Abstract — **Today, Integrated Gate Commutated Thyristors (IGCTs) are widely used for different applications such as medium voltage drives (MVDs) and interties. Application specific devices have been developed such as reverse conducting IGCTs for voltage source inverters (VSIs) [1] and reverse blocking IGCTs for current source inverters (CSIs) [2]. MVD switching frequencies are in the range of 500 Hz to 1 kHz and the trade-offs between switching losses and on-state voltage drop are optimised accordingly.**
In other applications, such as breakers, the switching frequency is lower and can range from a single shot (static breakers) to a few hundred Hz and IGCTs with very low on-state voltage drop have recently been developed for these applications [3]. While low on-state 4.5 kV devices for breakers have been available for some time new 6 kV IGCTs have recently been developed for induction melting and will be presented at the end of this paper.

I INTRODUCTION

Resonant inverters are widely used for induction heating. A resonant circuit is excited by either applying a voltage or current at, or close to, the resonant frequency of the LC circuit. Typical resonance frequencies and output power are shown in Fig. 1. The switching frequency decreases with increasing power.

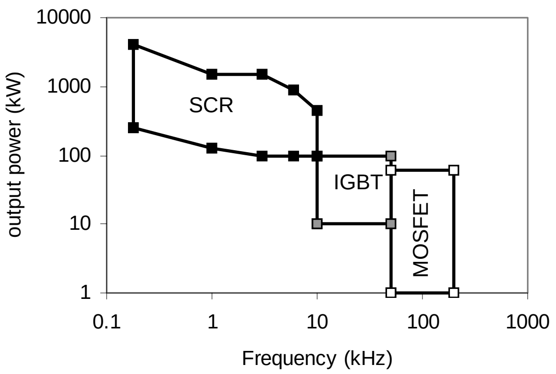


Fig. 1. Typical inverter frequency and output power

In the power range above 100 kW, the dominant semiconductor is the thyristor because of its high current capability and low losses, resulting in highest conversion efficiency. The topology used is frequently that of the current source resonant inverter (parallel resonance). Since the frequencies are too high for phase-control thyristors, these are not suitable because of their long turn-off times (t_Q). To reduce t_Q, thyristors are specially designed as fast turn-off thyristors. However, t_Q is a function of blocking voltage since stored charge in the device depends on silicon thickness. The t_Q of high-voltage thyristors is typically in the range of 200-500 µs and above the requirements of most applications. Reduction of t_Q is possible through lifetime control, but this results in high on-state voltages and turn-on losses due to the increased plasma spreading time which can result in hot spots and cooling problems. Lower-voltage, fast turn-off thyristors have acceptable turn-off times for these applications and many designs use lower voltage fast turn-off thyristors in series connection. The drawback to this solution lies in the increased complexity due to the high number of semiconductors, coolers, snubbers and gate-units and the additional costs of mechanical assembly.

The trend has therefore been to replace load-commutated devices (thyristors) by self-commutated devices such as GTOs and IGBTs as such switches can effectively operate at zero (or negative) t_Q. This trend is driven principally by the above mentioned issues but also, in more recent times, by concerns about the long-term availability of fast thyristors.

II IGCTs AND THYRISTORS

The IGCT, like the thyristor and the GTO, has a four-layer npnp regenerative structure. (Fig. 2). The main difference between thyristors and IGCTs lies in the cathode structure. Typical for the thyristor is a shorted cathode structure. The displacement current resulting from applied dv/dt will flow through the cathode shorts. If a critical current is exceeded, the voltage drop over the cathode shorts will lead to injection of electrons from the cathode emitter and uncontrolled triggering of the device, leading to device failure, will result. The cathode shorts are designed such that the thyristor is immune to dv/dt in the off state of the thyristor up to a specified level. However, after turn-off of the thyristor by current commutation, the charge carrier density decays slowly through recombination. While the device is still flooded with charge carriers, it is vulnerable to dv/dt and positive bias in general. Therefore the turn-off time t_Q is specified during which the device may not be exposed to dv/dt.

In the GTO and IGCT, the p-base is connected to the gate-driver via a very low impedance and during the off-state a negative voltage of 20 V is applied. Displacement current generated by a dv/dt will flow from anode-to-gate and into the gate-driver, by-passing the cathode and avoiding re-triggering of the device.

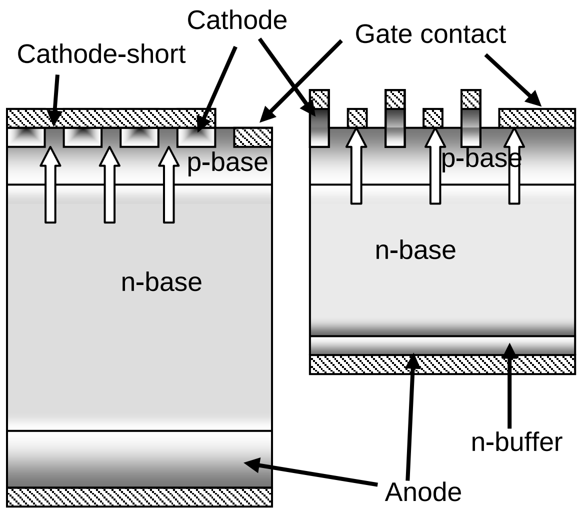


Fig. 2 Structure of fast turn-off thyristor and IGCT. Displacement currents generated by dv/dt indicated by arrows.

In contrast to the thyristor the IGCT may additionally be gated off and in this respect, IGCTs allow an extra degree of control flexibility as compared to the thyristor.

Fig. 1 compares a thyristor with an IGCT, both of which can be realised as symmetric or asymmetric blocking devices. VSIs preferentially require reverse conducting devices or alternatively, for higher powers, asymmetric devices with discrete anti-parallel diodes. CSIs require reverse blocking capability or series connected diodes if asymmetric switches are used.

Since asymmetric devices are thinner and generate lower losses, they have higher current ratings than symmetric devices and can be operated at higher junction temperatures. One approach presented in the literature [4] is to make all devices asymmetric and to encapsulate the GCT wafer with its series diode in the same housing when realising symmetric blocking devices for lower rms currents but to encapsulate them separately (2 press-packs/three heat-sinks) for higher ratings.

III PARALLEL RESONANCE

A current source resonant inverter is shown in Fig. 3. The resonant circuit consists of a capacitor C_l, and an inductor L_l with series resistance R_l representing the load. The resonant frequency of this oscillator is given by:

$$f = \frac{1}{2\pi\sqrt{L_l C_l}}$$

Typical component values of $L_l \approx 500\mu H$, $C_l \approx 5\ mF$ and $R_l \approx 100 m\Omega$ lead to frequencies in the range of 150 - 200 Hz.

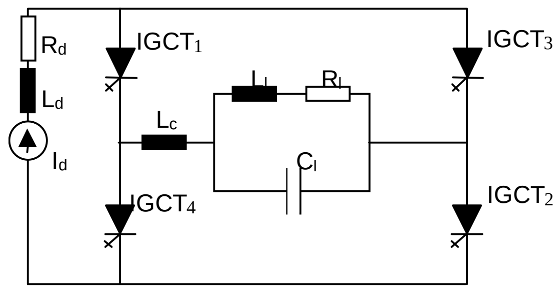


Fig. 2 Basic circuit of the current source resonant inverter.

In steady-state operation, the voltage V_{cl} across capacitor C_l is sinusoidal. Resistor R_l damps the oscillation and represents the energy absorbed by the furnace load. While L_l and C_l are fixed, R_l depends on the furnace operating point, i.e. on the loading of the crucible and the temperature and state of the metal. The energy supplied to the load (resistor R_1) is controlled by the current I_d. L_c is the commutation inductance limiting di/dt when the current is commutated from one diagonal switch pair (e.g. $IGCT_1$ and $IGCT_2$) to the other diagonal ($IGCT_3$ and $IGCT_4$) and vice versa. The IGCTs shown in Fig. 2 may be symmetric types or series connected asymmetric IGCTs and diodes either assembled in one housing (e.g. ABB types 5SHZ 08F6000 and 5SHZ 15H6000) or discrete asymmetric IGCTs and series diodes for higher powers as will be described later. The value of L_C, including the stray induction of the commutation loop, is chosen such that the critical di/dt of the series diode is not exceeded. A small RC snubber limits dynamic over-voltage in the unclamped AC circuit of the CSI.

Simplified voltage and current waveforms for a reverse blocking IGCT are shown in Fig. 3. Initially the IGCT blocks the sinusoidal voltage given by the resonant circuit. At t = t_1 an IGCT diagonal pair is turned on and the current commutates to these switches with a di/dt given by inductor L_C. Turn-on losses for the IGCT are negligible since it turns on like a bipolar transistor with an inductance in its collector. After a half period, the IGCTs in the alternate diagonal branch are turned on. Since the voltage V_{cl} is negative at this point, the device turns off into negative voltage. The time delay between firing the IGCTs in the on-going diagonal and the resonant zero crossing of V_{cl} defines the reverse voltage. Typically the reverse voltage will be much smaller than the forward blocking voltage. In the case of discrete devices, different voltage ratings for the IGCT and the diode can be chosen. Charge carriers injected into the IGCT during the conduction phase will be partially extracted by the reverse current through the series diode and the bulk of the rest will recombine during the reverse blocking phase. When the voltage becomes positive at the subsequent zero crossing of V_{cl}, the remaining carriers are extracted by the reapplied voltage from anode-to-gate generating turn-off losses.

Turn-on timing is critical in the case of thyristors. If the time interval of t_Q between triggering of thyristors in the on-going diagonal and the resonant zero crossing of V_{cl} is not respected, the off-going thyristor will fail. In the case of the IGCT, this is not critical since the IGCT has no t_Q requirement.

The turn-off gating of the off-going device can be realised by turning diagonal devices on and off simultaneously. Since the turn-off delay time t_{DOFF} is always greater than the turn-on delay time t_{DON} there is no danger of an open circuit in the DC current link.

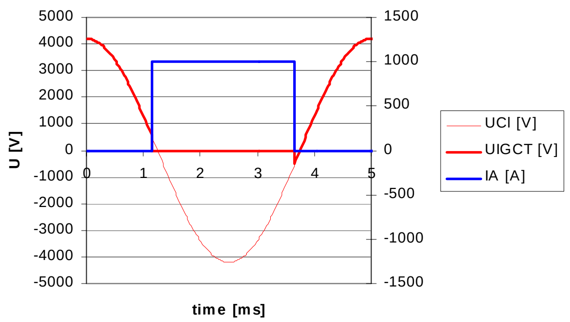


Fig. 3 IGCT current and voltage waveforms for circuit shown in Fig. 2. (switching frequency = 200 Hz)

IV TEST RESULTS

The application conditions for the IGCT in the current source resonant inverter are different from the one in the current source inverter described earlier [2]. In the case of a series connection of discrete IGCTs and diodes, the main losses in the IGCT will be due to on-state voltage drop. The main commutation will be load commutation. To obtain experimental results about turn-off *timing* and turn-off *time* t_Q in the resonant inverter, a 6 kV 91 mm IGCT with low on-state voltage drop (5SHY 40L6011) was tested. To allow independent variations of turn-off timing and turn-off time t_Q, an Auxiliary Resonant Commutated Pole converter (ARCP), shown in Fig. 4, was used for the measurements [5, 6]. For application in the current source resonant inverter, the behaviour of the IGCT as a zero current switch is of interest. Therefore the IGCT was measured at the position of the auxiliary switch AS1.

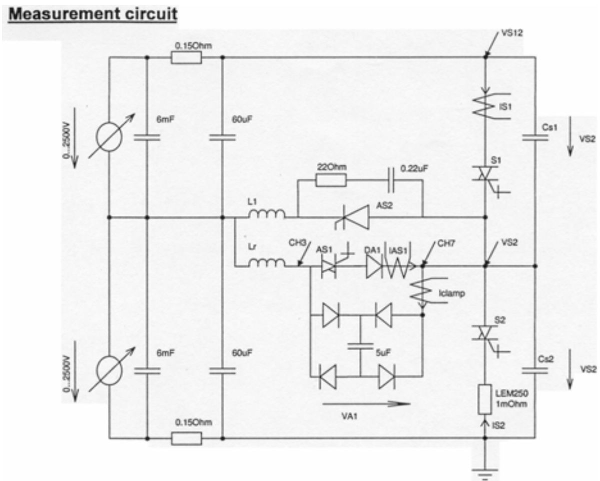


Fig. 4 ARCP soft switching test circuit for t_Q testing

Turn-off of 1 kA into a reverse voltage is shown in Fig. 5 using the ARCP. The gate is biased off 20 µs after zero cross and a forward voltage is reapplied at 350 V/µs a further 20 µs later (i.e. 40 µs after zero cross). The applied forward dv/dt is much higher than described in Fig 3 corresponding to higher switching frequencies. As shown in [6] the turn-off losses due to the reaplied forward voltage is a strong function of dv/dt. During the reverse recovery of the series diode, I_{RR} is flowing through the anode and the gate of the IGCT. During reverse recovery the gate-driver turns-off the gate back-porch current and the gate-voltage goes slightly negative. After recovery of the diode, the back-porch current is reapplied.

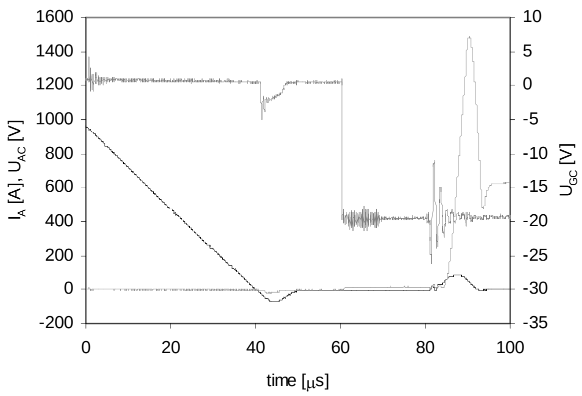


Fig. 5 Turn-off into reverse voltage of 6 kV IGCT (—I_A, —U_{AC}, —U_{GC})

Since the charge extracted by the reapplied forward voltage decreases with time due to charge carrier recombination, turn-off energy, defined here as E_{TQ}, decreases with increasing t_Q.

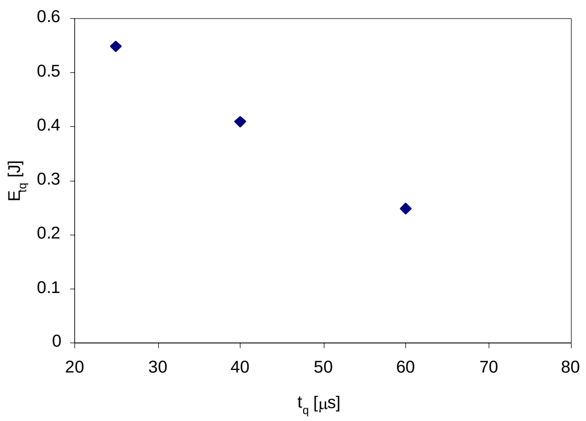


Fig. 6 Turn-off energy loss E_{TQ} as a function of t_Q.

Fig. 6 shows the dependence of turn-off energy on t_Q for an IGCT with low on-state voltage drop. Depending on the desired switching frequency of the application, the charge carrier lifetime of the device can be reduced to achieve a different trade-off between on-state voltage drop and turn-off losses.

Fig. 7 shows turn-off of an IGCT with "negative turn-off time". This corresponds to gate turn-off of the IGCT into positive voltage, as one would expect in a conventional (non-resonant) inverter. The positive (but falling) anode current still forward biases the series diode. In this test, a first phase of charge extraction in the device occurs as the device builds up forward voltage.

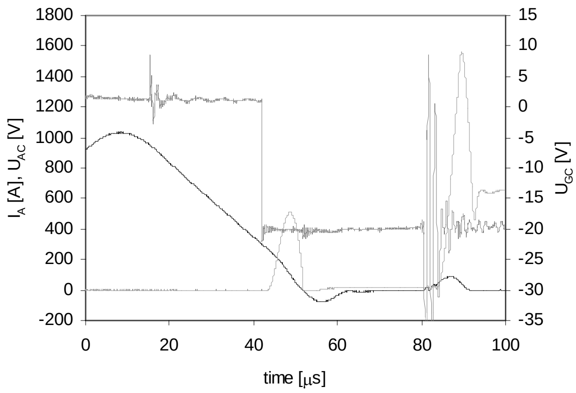


Fig. 7 Turn-off of IGCT with zero t_Q. (—I_A, —U_{AC}, —U_{GC})

However, charge is not removed completely during this phase since the voltage follows V_C and quickly falls to zero causing the series diode to undergo reverse recovery allowing a second phase of charge extraction limited by the diode's reverse recovery. The device is finally depleted when positive voltage is reapplied after the zero crossing of V_C at about 80 µs at which point a positive displacement current can be observed completing the third phase of charge extraction. In this case the total turn-off losses are higher than for positive t_Q.

Fig. 8 shows the dependence of E_{TQ} on turn-off timing Δt_{DOFF} for a constant t_Q of 40 µs where Δt_{DOFF} is defined as the gate turn-off time with respect to the point of current cross (e.g. -10 µs in Fig. 7).

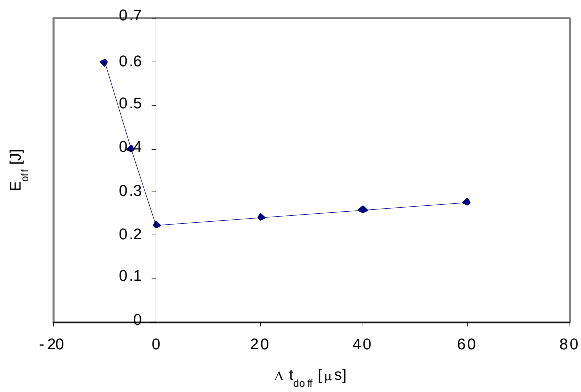
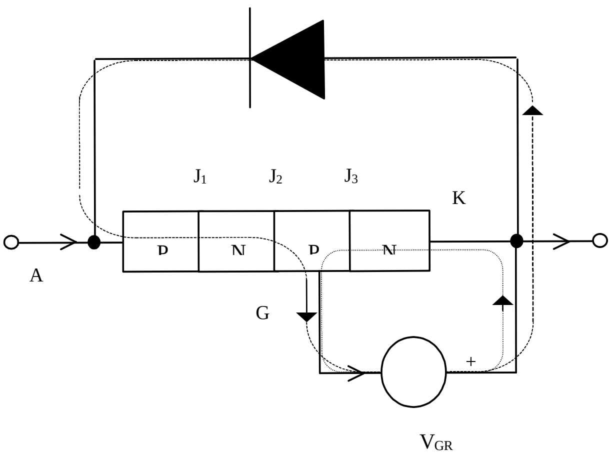


Fig. 8 E_{TQ} as a function of Δt_{DOFF}

The increase of E_{TQ} with increasing turn-off delay is due to the fact that less stored charge is removed by the gate current flowing through the anti-parallel diode of the IGCT in the ARCP test circuit (Fig. 4). This is illustrated in Fig. 9, which shows the gate current path (in the case of a forward biased anti-parallel diode) flowing *into the anode*. In contrast to the current source resonant inverter, in the voltage source resonant inverter the current path through the parallel diode is available.

Fig. 9 Gate current path through an antiparallel diode in



the ARCP test circuit.

V DEVICE RATINGS

The new devices specifically developed for high power resonant inverters for induction heating or melting are initially available as a chip-set consisting of a discrete diode and a discrete asymmetric IGCT of 6 kV blocking capability.

Ratings are given for a commutation inductance of 5 µH and a RC snubber of 5 Ω/0.4 µF. I_{TGQ} and I_T = 1500 A and V_D = 3000 V. This device is optimised for low switching frequencies.

IGCT type 5SHY 40L6011

V_{DRM}	6000 V	from 0 to 125°C
E_{ON}	0.5 J	di/dt = 1500 A/µs
E_{OFF}	12 J	3 kA, 3kV, 125°C
V_T	2.2 V	At 3 kA, 125°C
R_{TH}	9 K/kW	double side cooled

Note:
The energy loss E_{TQ} when the IGCT is turned off into negative voltage followed by forward voltage after time t_Q is, of course, smaller than E_{OFF} which is a conventional turn-off condition.

Fast Diode type 5SDF 12L6004

V_{DRM}	6000 V	from 0 to 125°C
E_{OFF}	14 J	3 kA, 3kV, 125°C di/dt = 1500 A/µs
V_F	2.5 V	At 3 kA, 125°C
R_{TH}	7 K/kW	double side cooled

Both these devices have 85 mm pole-piece diameters and nominal mounting forces of 40 kN allowing them to be mounted mechanically in the same stack assembly. The “chip-set can be seen in Fig. 10.

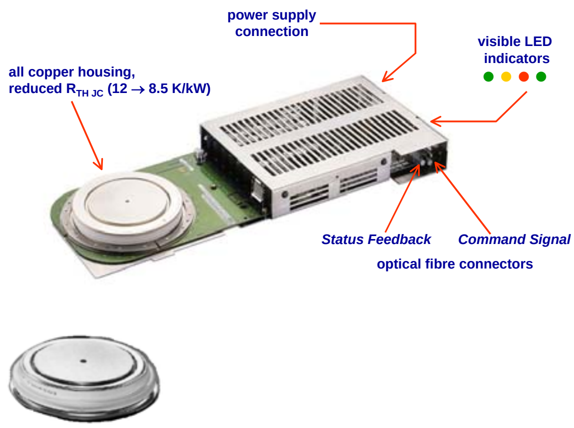


Fig 10 6kV/91 mm IGCT/F-Diode chip-set for CSI and VSI resonant inverters

CONCLUSIONS

IGCTs have found their way into a multitude of applications in the short time that they have been available on the market. Now they are about to enter the world of resonant power inverters and their first use will be for current-source induction melting furnaces although the two chip-set is intended to meet the needs of both series and parallel resonance (voltage and current source inverters).

The combination of:

- low conduction and switching losses
- high current and voltage
- low t_Q and high dv/dt
- high peak and high rms currents

allows substantial cost and performance improvements compared to the conventional series-connected fast turn-off thyristors currently used.

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