THE IGCT - THE KEY TECHNOLOGY FOR LOW COST, HIGH RELIABLE HIGH POWER CONVERTERS WITH SERIES CONNECTED TURN-OFF DEVICES

P. K. Steimer, H. Grüning, J. Werninger
R&D Drives and Power Electronics
Dept. IA
ABB Industrie AG
CH-5300 Turgi, Switzerland

Abstract: The IGCT technology (Integrated Gate-Commutated-Thyristor), which is based on the concept of the hard driven GTO, reduces inherently the storage time of the turn-off device to 1us and allows the robust series connection of high power turn-off devices. The homogenous operation, especially during turn-off, allows the reduction or even elimination of the dv/dt snubber. Together with an improved device design (buffer layer, transparent anode) the inverter losses and costs are dramatically reduced. The first application of this technology in a 100 MVA intertie based on the 1st generation of series connected IGCTs is discussed and operational experience is presented.

Keywords: GCT, IGCT, Series Connection,
Hard driven GTO, Intertie

INTRODUCTION

Static frequency converters with high efficiency and state-of the-art performance can be found today in a lot of applications up to a very high power level. The main applications can be found today in traction, industry, power transmission and power generation. Power electronics products and systems are still in a phase of continuous innovation.
In the last decade a strong technology push was initiated by the GTO technology. In the inverter module the GTO technology asked for a special environment for the semiconductor, like

- low inductive dv/dt snubbers
- di/dt snubbers
- low inductive DC-link
- reliable GTO drivers (gate units)

The switching frequencies of the GTOs was typically limited due to device and snubber losses to a maximum value of about 300 Hz. Additionally either the GTO inverter efficiency was relatively low or costly regenerative snubbers were needed for high efficiency solutions. But regardless of this additional demands, limitations and costs the GTO technology has found its interesting applications.

But again we are all aware of a new revolution taking place in the area of high power semiconductors and its applications. New high power semiconductors like HVIGBTs (High Voltage Insulated Gate Bipolar Transistor) and the new emerging IGCT (Integrated Gate Commutated Thyristor) are getting available for the user (Linder at al [1]). Especially in the field of high power applications (0.5 MVA up to several 100 MVA) the concept of the IGCT has the potential to offer the following significant advantages in comparison to all other today available turn-off devices:

- lowest costs per MVA
- lowest losses per MVA
- lowest parts count per MVA and
- highest reliability per MVA.

Due to this advantages is must be expected, that the IGCT will continue to find fast its place in all high power applications. Typical applications will be

- Medium voltage adjustable speed drives
- High dynamic rolling mill drives
- railway interties
- high power traction
- variable speed power generation
- high voltage DC transmission

- Custom Power applications like
  - dynamic voltage restorers
  - active filters
  - energy storage systems
- FACTS applications like
  - unified power flow controller
  - static Var compensators

In the field of high power electronics one important key technology, which is inherently offered by the IGCT, is the cost-efficient and robust series connection of turn-off semiconductors (Steimer et al [2]). This series connection is either needed to reach the targeted medium or high voltages levels or it is needed to reach the higher power levels.

The first breakthrough of the IGCT technology has taken place mid of 1996 with the successful commissioning of the first high power application with series connected IGCT devices of the 1st generation. This first 100MVA railway intertie (Boeck et al [3]) will be presented in detail in this paper. The excellent operational experience since mid of 1996 will be explained. Additionally the future potential for innovation with the use of the now available 2nd generation of IGCTs will be discussed.

THE INTEGRATED GATE COMMUTATED THYRISTOR

A cost-effective realisation of the IGCT (press-pack GCT device with integrated gate driver) is shown in Fig. 1. To reach the needed high di/dt-values of several 1000A/us in the gate current a low-inductive housing of the GCT is the key innovation (Grüning [4]).

The turn-off of the IGCT is a a very fast transient. In about 1µs the gate current is increased on the level of the maximum turn-off current Itgqm. The cathode current is reduced to zero before the anode voltage raises. The turn-off of the device happens completely in a transistor mode, which guarantees a completely controlled and homogenous turn-off. No current filamentation phenomena, as known from GTO technology, exists with the IGCT technology. The turn-off happens so fast, that the device realizes too late that it is in fact a four layer thyristor device and stays in the transistor mode during turn-off. Therefore the only limitations experienced are in the silicon. The device can be operated directly at the phyiscal limits defined by this material.

Fig 1: The IGCT - the Gate Commutated Thyristor with its integrated gate driver as used in the 100 MVA intertie

Due to the turn-of in a transistor mode very high dv/dt robustness is experienced. This feature allows inherently to reduce or to get rid of the dv/dt snubber. A snubberless operation of the IGCT can be found in fig. 2, where the turn-off of 3kA with a 1st generation IGCT device is shown.

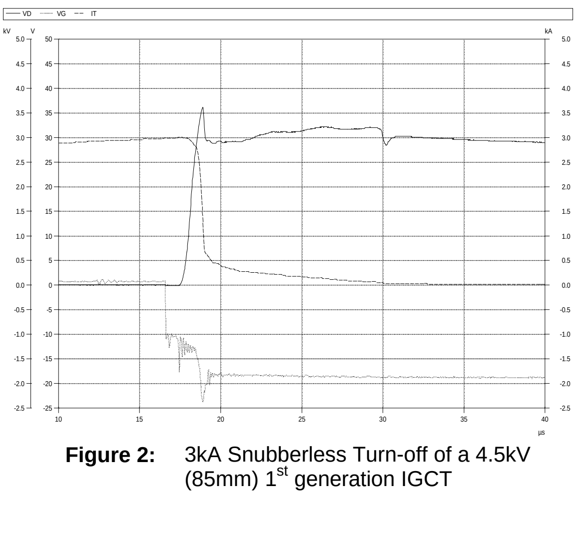

Figure 2: 3kA Snubberless Turn-off of a 4.5kV (85mm) 1st generation IGCT

3kA, 4.5kV, 125 °C, 85mm	GTO	IGCT 1st gen.
On-state voltage Vtm	3.2 V	3.2 V
Turn-on di/dt	500 A/µs	3000 A/µs
Turn-on energy Eon	5Ws	1 Ws
Turn-off energy Eoff (3 kA)	10 Ws at 6µF	10 Ws at 6µF 13 Ws at 0µF
Snubber cap. Cs (3 kA)	6 µF	0 to 6µF
Max turn-off current ITGQM	3 kA	3 to 6kA
Gate drive power (500 Hz)	80 W	30 W
Gate stored charge Qgq	8000 µC	2000 µC
Max. turn-off dv/dt	500V/µs	3-4000V/µs
Storage time ts	20 µs	1 µs

TABLE 1: Comparison between GTO and 1st gen. IGCT

In regards of the high power applications with series connected devices the following improvements due to the IGCT technology are of importance

- the storage time of the IGCT is reduced to 1 µs and therefore defining the base for the simple and robust series connection of IGCTs
- the dv/dt-snubber and therefore inverter losses can be considerably reduced or negelected due to the completely homogenous operation of the IGCT.
- the gate drive power is considerably reduced due to the lower gate turn-off charge
- the gate drive costs are reduced

Based on further innovations in the semiconductor technology the 2nd generation IGCT based on a buffer-layer, transparent anode design has been developed. In the new design the electrical field in the blocking pn-junction is rather a constant. This is achieved with the buffer layer in the device. With this design the same blocking voltage can be achieved with a thinner silicon, resulting in a more efficient device.

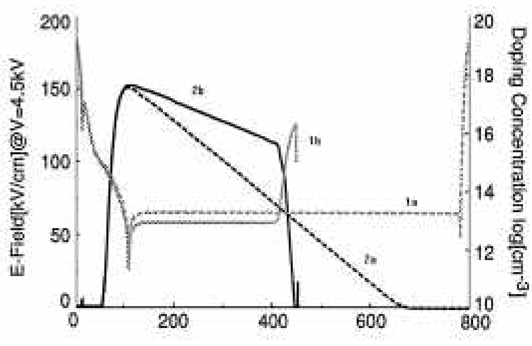

Figure 3: Electrical field and doping profiles of the IGCT

1a: doping profile of 1st generation IGCT
2a: electrical field of 1st generation IGCT
1b: doping profile of 2nd generation IGCT
2b: electrical field of 2nd generation IGCT

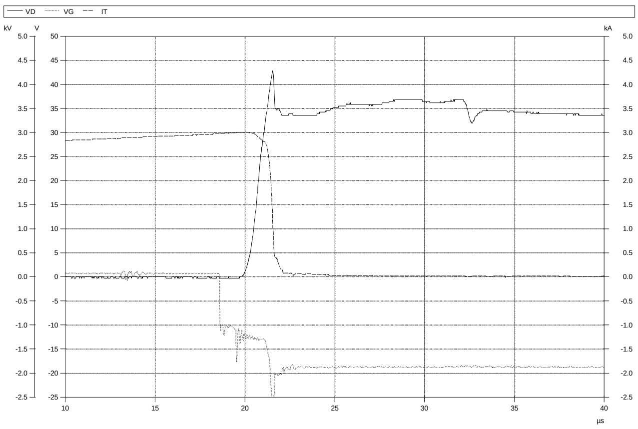

Figure 4: Snubberless turn-off of 3kA with a 2nd generation IGCT

The combination with the new transparent anode design leads to significant reduction of the needed gate trigger current and reduces additionally the costs of the gate driver by increasing the overall reliability due to the lower power consumption (see table 2).

In figure 4 the snubberless turn-off of a 2nd generation, low loss IGCT can be seen. The low switching losses (see table 2) are a result of the thin device, the new shape of the electrical field in the device (see fig. 3) and the corresponding small and short tail current (Gruening et al [5]).

3kA, 4.5kV, 125 °C, 85mm	IGCT 1st gen	IGCT 2nd gen.
On-state voltage Vtm	3.2 V	1.9 V
Turn-off energy Eoff (3 kA)	10 Ws at 6µF 13 Ws at 0µF	5 Ws at 3µF 10 Ws at 0µF
Gate drive power (500 Hz)	30 W	15 W

TABLE 2:
- Comparison between 1st generation
- IGCT and 2nd generation IGCT

THE SERIES CONNECTION OF IGCTs

The power semiconductor development has to face physical and economical limits in the continuous development of the blocking voltages and the maximum turn-off currents. Typical maximum values for the GTO technology are today 6kV dynamic blocking voltage and 6kA turn-off current. This corresponds to a maximum inverter power in an NPC inverter without series connected devices of about 15 MVA. The newest IGCT technology includes inherently the possibility to further expand this values. But this innovation will be not enough for the future demands. The future power electronics system market is asking for converter powers, which clearly exceed this value of 15 MVA. Inverter ratings of several 100 MVAs will be needed in the near future.

To reach higher power ratings one solution is to divide the total power between several subsystems. Such installations are considerably more complex then one-single high-power converter. What is more, they are more expensive to purchase and operate, exhibit lower efficiency and reduced full-power avaliability, and take up more space. The key innovation for the future high power applications is to introduce the series connection of turn-off devices.

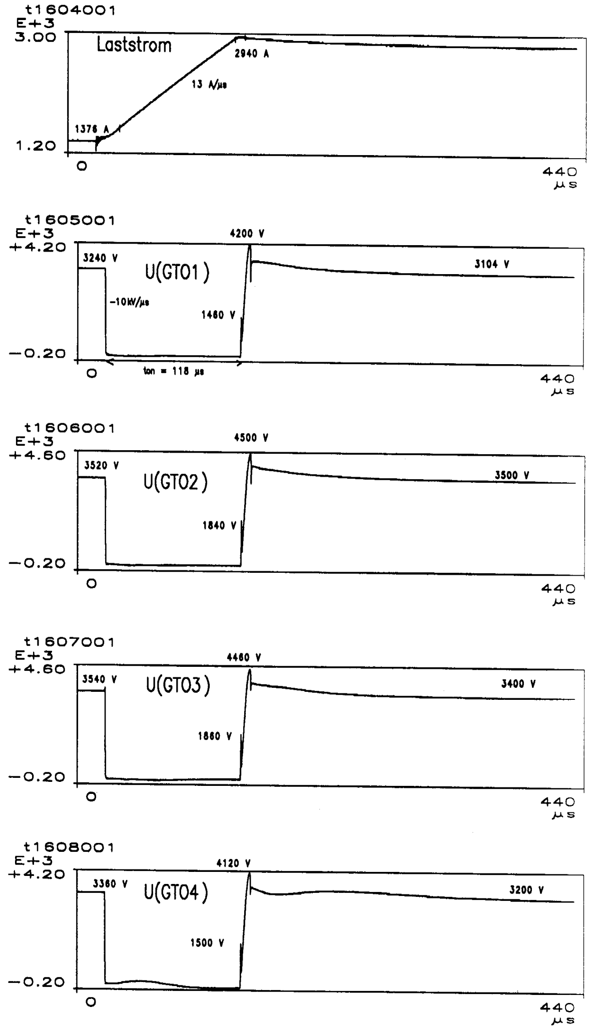

Figure 5: Turn-off of four series connected 3kA GCTs at a DC-link voltage of 13.2 kV

This series connection of turn-off devices also offers the greatest benefits in terms of first-time and operating costs. Series-connected thyristors are a proven HVDC technology and such configurations have been used successfully for decades.

The concept of the IGCT, which inherently allows, due its very short storage time of 1µs, the robust series connection of semiconductors, is the key technology for new high power inverters.

Based on the series connection the well-proven way to ensure maximum availability is to connect more IGCTs then necessary in series. This makes sense since it improves the installation in a number of ways:

- in the event, that an IGCT or an antiparallel diode fails the installation will continue without interruption. This is because the IGCT as a presspack device is designed to fail short-circuit. The failure is detected by an electronic circuit and signalled via fiber optic cables. The failed device can be replaced later, during routine maintenance.
- the addition of the redundant IGCT reduces the voltage load of each individual device, including any eventual snubber circuit. It is known that the lifetime of the individual device depends strongly upon the voltage stress. When it is reduced for example by one third, the average lifetime of the IGCT is increased by a factor of about 20.

- the incorporation of redundant IGCT reduces the risk of a shoot-through in a converter phase, therefore allowing the construction of fuseless high power converter and improving converter reliability and efficiency. Accordingly, shoot-through is very unlikely. but the converter is nevertheless constructed to withstand the mechanical stresses during such fault conditions.

The series connection of turn-off devices based on the 1st generation of IGCTs has been sucessfully tested in 1994. A complete H-brigde with two converter phases consisting of 4 series connected IGCTs (totally 16 devices) has been tested in the power testlab. The series connection of IGCTs has been thoroughly and systematically tested incl. accelerated life-time tests and verification by means of comprehensive calculations and simulations.

In Fig. 5 the oscillogramm of the simultaneos turn-off of 4 series connected IGCTs can be seen. Due to the very short storage time of the IGCT (1us) and therefore the small tolerances in turn-off times of the different devices (less then 0.2 us) a very good voltage sharing of the series connected devices is reached. To reach low dynamic overvoltages on the IGCTs the high power phase module was constructed very low-inductive. Due to the very homogenous operation of the IGCT the spike voltage of the turn-off device is no more a dimensioning factor. The spike voltage did reach in this test values of 1500V.

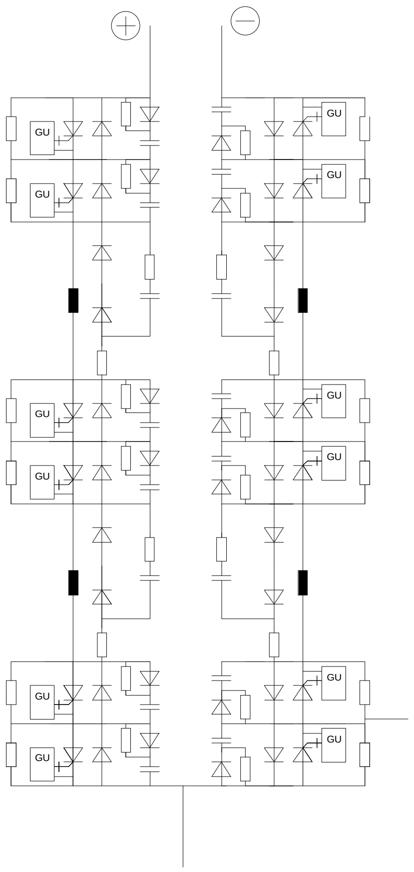

Figure 6: High Power IGCT Inverter Module (Ns = 6)

For the first commercial application of the series connected IGCTs in a 100MVA intertie a new high power IGCT inverter module was developed. For the applications in the high power field a low-inductive, cost effective, water-cooled inverter module with an increased number of 6 series connected IGCTs was developed. Each 4.5kV IGCT can be loaded with a maximum stationary DC voltage of 3kVDC. The design of the high power inverter module is normally selected to be a Ns = 5+1 design. The realisation of a redundant design leads to a considerable increase of the availability of the inverter. The redundant design is a must in ultra high power application to reach the needed reliability. In figure 7 the High Power IGCT Inverter Module as used in the 100 MVA intertie can be seen. The Inverter Module integrates a single phase leg. The IGCT inverter module, based on 1st generation IGCT, is eqippped with reduced dv/dt-snubbers of a simple RCD-type. The supply of the gate drivers is done over special separation transformers.

The future innovation due the use of the 2nd generation of IGCTs is expected to be

- further reduced losses of the inverter module
- elimination or further reduction of the dv/dt snubbers
- higher switching frequencies upto 1kHz or higher
- supply of the IGCTs directly on the potential due to the reduced gate drive power

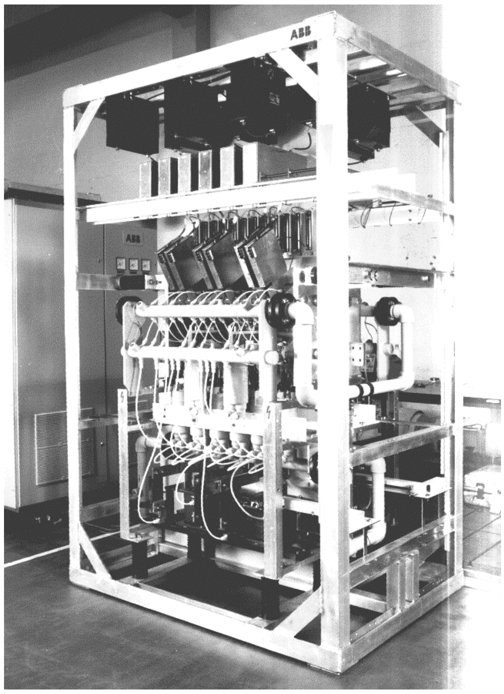

Figure 7: High Power IGCT Inverter Module (Ns = 6)

THE TECHNICAL CONCEPT OF THE 100 MVA INTERTIE

In spring 1994 ABB Industrie AG received the order for an installation of a 100 MVA back-to-back intertie between the 3-phase 50 Hz grid and the one-phase $16^2/_3$ Hz railway grid in Germany (figure 8). ABB was seen by the customer as the clear leader in high power IGCT inverter technology. For the first time the series connection of high power IGCTs was offered by ABB. This concept was well received due to its simple and robust solution of the series connection of IGCTs. The commissioning was completed in july 1996 and the installation was inaugurated in september 1996.

The technical concept of the railway intertie based on a VSC (Voltage Source converter) is already in continues operation for two 20 MVA frequency converters with the Swiss Federal Railway (SBB). The installations at Giubiasco are based on conventional GTO technology without series connection (Gaupp et al [6] and Mathis [7]).
For the 100 MVA Intertie the following technical innovations have been added:

- 1st generation IGCTs with its low-inductive housing
- series connection of six IGCTs
- low-inductive high power IGCT inverter valve
- fuseless high power IGCT inverter.

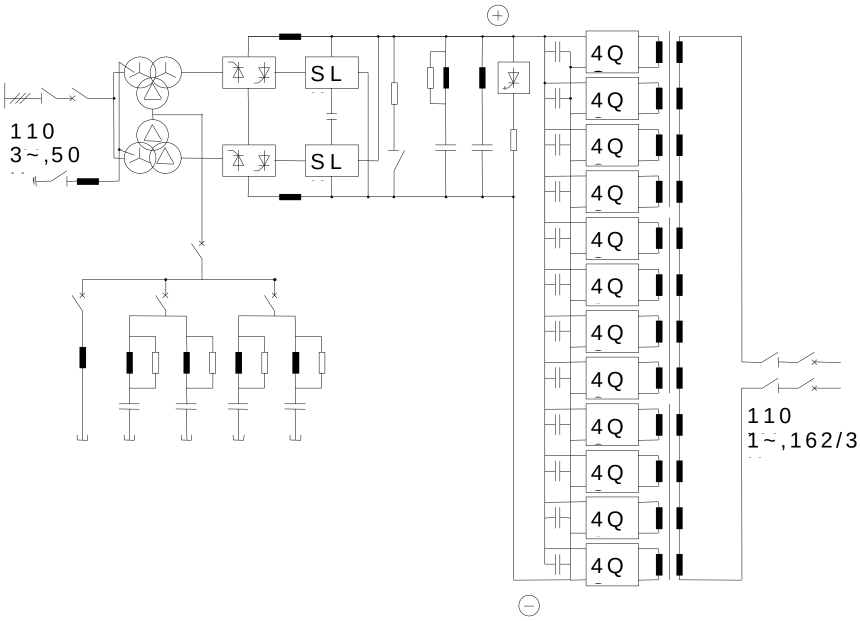

Figure 8: The 100MVA Intertie based on series connected IGCTs

Especially in the High Power Inverter Module for the 100 MVA intertie a high degree of innovation was included (IGCT, series connection, new low-inductive inverter design). New methods for the verification of the power electronics development already in an early development phase have therefore been applied (Steimer et al [8]).

To fulfill the requirements of the customer the following technical technical concept for the frequency converters (fig. 1) based on a VSC has been choosen:

– The converter on the 3-phase 50 Hz side is based on a conventional antiparallel 12-pulse thyristor bridge
– In combination with harmonic filters the 50 Hz line impact is minimized to the specified levels.
– The thyristor converter feeds directly into a 10 kV DC-link, which is equipped with an additional $33^1/_3$ Hz filter for the elimination of the power fluctations generated by the one-phase $16^2/_3$ Hz grid
– The IGCT inverter on the railway side consists of 288 IGCTs arranged in 24 fuseless phase modules in a Ns = 4+2 design. Two phase modules are feeding into a double-fed transformer winding. The twelve windings of the railway side transformers are used to built a 25-level inverter. This multi-level concept allows the filterless operation of the railway side GCT inverter.
– four DC-voltage choppers with totally 24 IGCTs

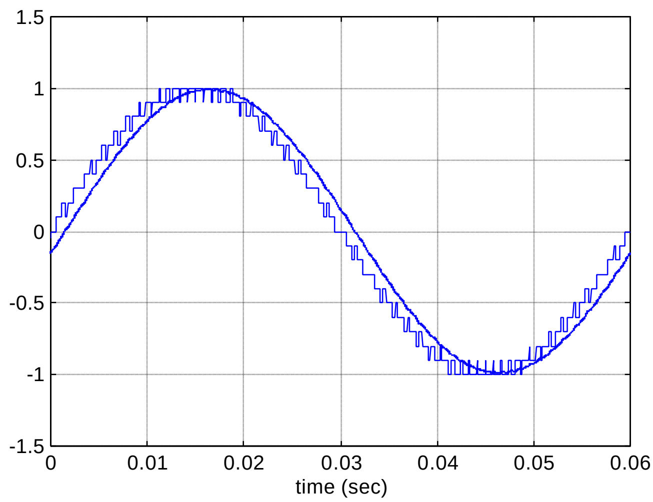

Figure 9: Inverter voltage and current (smoothed by the short-circuit impedance) on the $16^2/_3$ Hz railway side

OPERATIONAL EXPERIENCE

The first 100MVA installation based on the IGCT technology is now in commercial operation since mid of 1996. The operational experience over 9 months is excellent. Out of the more then 300 IGCTs, which are installed in this intertie only one single unit has failed upto now due to a contact problem of a light emitting diode. The expected high reliability figures of the IGCT technology have been successfully proven (500 FIT per GCT place).
This reliability values are impressive and benefit definitely from the reduced voltage stress due to the series connection of IGCTs with redundant devices. The further component reduction due to the snubberless operation potential will improve the realibility even further in the future (Grüning and Ødegård [9]).
The high reliability of the single IGCT is the important basic brickstone. This high IGCT reliability values combined with the series connection of this turn-off devices for realizing redundant converter design will be the backbone of future high power electronics converter especially for the new emerging FACTS and Custom Power markets.

CONCLUSIONS

The IGCT has shown its highly reliable operation in its first 100 MVA application in Bremen. A second 130 MVA intertie based on the same technology has been ordered in december 1996 for feeding the $16^2/_3$ grid of the Federal German Railway close to Munich. This second order was received due to the very good experience with the first 100 MVA reference installation.

The IGCT, an important european contribution to power electronics, is on its way to be the dominant device for all medium to high voltage, high power applications from 0.5MVA upto 100MVA in the near future. It inherently includes the needed key technology of simple and robust series connection of high power turn-off devices for medium voltage and high power applications. Due to its additional advantages of lowest costs, lowest complexity and highest efficiency, compared with any other turn-off device, the IGCT has to fear no real competition in this power range.

Due to the recognized importance of the IGCT for the high power electronic applications the world-wide technology launch with newest 4.5kV IGCT devices has taken place in spring 1997. Today two major high power semiconductor manufacturers are ready to deliver the IGCT devices to the open power electronics market.

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