IGCTs – megawatt power switches for medium-voltage applications

Designing equipment to switch megawatts of power at medium-voltage levels is a difficult task. The inherent characteristics of the two available silicon switching technologies, Gate Turn-Off (GTO) Thyristors and Insulated Gate Bipolar Transistors (IGBTs), force design trade-offs that increase the cost and complexity of power control systems. GTO thyristors not only require complex peripheral circuitry to ensure reliable operation but also switch at low frequency. Designers of IGBT-based systems at medium voltage must deal with high losses and balance an increase in the number of components with the need to ensure availability. ABB's new Integrated Gate Commutated Thyristor (IGCT) technology overcomes the drawbacks of both the GTO thyristor and the IGBT, and includes all the circuitry required to make the power device reliable and easy to design into medium-voltage applications.

ABB manufactures high-power GTO thyristors and IGBTs for use where reliability is of paramount importance. Power control system applications include industrial motor drives, train and ships' propulsion, and transmission lines **1**, **2**. Many of these applications are at the medium-voltage levels of 2.3, 3.3, 4.16 and 6.9 kV.

Development of power silicon switches

ABB has invested continuously in the development and production of GTO thyristor and IGBT technologies, and the performance of both devices has improved steadily as a result **3**. In the last few years, a series of linked innovations has created a platform for the design and production of a power silicon switch which extends beyond the IGBT and GTO thyristor performance envelope. Known as the IGCT (for Integrated Gate Commutated Thyristor), it can switch more quickly and has lower losses than either the GTO thyristor or IGBT. More importantly, it has characteristics which enable electrical power system engineers to shrink the size and cost of medium-voltage systems while boosting their efficiency and reliability.

A better power switch

In the 30 years since their introduction, power silicon switches have increased steadily in complexity and capability. The first silicon-controlled rectifiers could switch power off only at the end of an AC cycle. Progress came with the GTO thyristor, which can switch at any point in the cycle. The introduction of IGBTs brought faster switching, but at present their switching losses are acceptable only at low voltage levels. The tendency over the years has been for the designers of all these devices to concentrate mainly on the power switching itself, so that little attention has been paid to the complexities involved in real-world applications.

GTO thyristors consist of thousands of individual switching elements fabricated on a silicon wafer. Losses occur in all four conditions of operation (on, off, switching on, switching off). At medium voltage, GTOs exhibit very low on-state losses and reasonable turn-off losses. However, due to switching being non-homogeneous, external snubber circuits are necessary for the switching operation. These snubber circuits take up more than half the volume of the final equipment and account for much of the design complexity, costs and losses.

Conversely, IGBTs have comparatively higher conduction losses but switch homogeneously, ie they do not need a snubber. However, they are not yet available for direct operation at all medium-voltage levels. To overcome this handicap, designers must connect low-voltage IGBTs in series, dramatically increasing the complexity, increasing losses and reducing system reliability. A converter designed for operation at 4.16 kV, for example, requires four series-connected 1.8 kV IGBTs per phase.

GTO thyristors can be produced economically for applications at most medium-voltage levels. It is anticipated that 3.3-kV and 4.5-kV IGBTs will become available and simplify the design of medium-voltage power circuits, but it is known already today that they will have high losses. To overcome these losses and the resulting heat build-up, the IGBTs

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will have to have a larger silicon area, and this will increase costs.

The ideal power switch would switch like an IGBT and conduct like a GTO thyristor, and it would have the low fabrication costs and high yields of the GTO thyristors. This is exactly what the IGCT achieves (*Table 1*).

The secret of IGCT technology

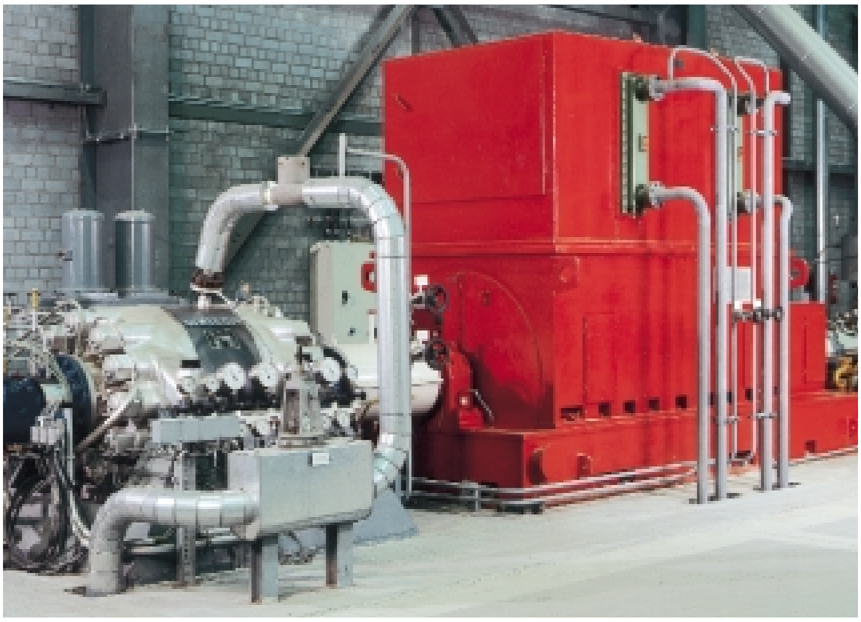
In IGCT technology, a combination of design innovations permits the thousands of individual power switching structures in a modified GTO thyristor to switch fast and simultaneously. What is more, the low on- and off-state losses inherent in thyristor designs are retained.

The first of two key innovations is the buffer layer design, which has allowed the on-state and switching losses to be reduced by a factor of 2 to 2.5 and makes the optimum doping profile of a GTO and a diode virtually identical. Previously, integrating a diode with a GTO has resulted in severe degradation of the diode's performance. Although the idea of the buffer layer is almost as old as the GTO itself, it has never been used before for the following reason: to reduce the switching losses, the charge stored in the device in the conducting phase has to be removed quickly at turn-off. In a conventionally designed GTO this function is performed by anode shorts, which provide a path for the electrons to flow out.

With the IGCTs, equipment designers can build more compact and less costly power control systems, eg static var compensators for utilities. **1**

Table 1:
IGCT technology combines the advantages of GTO thyristors and IGBTs

	GTO thyristor	High-voltage IGBT	IGCT advantages
Switching technology	• Available for most medium-voltage levels • Low on-state losses	• Switches at high frequency • Low switching losses • Snubberless • Integrated gate drive	• Switches at high frequency • Low switching and on-state losses • Snubberless • Available for most medium-voltage levels
Power circuitry	• Safe from catastrophic failure	• Low parts count at low voltage • Suitable for parallel and series connection at low voltage	• Safe from catastrophic failure • Proven reliability • Integrated diode and gate unit for low parts count • Suitable for parallel and series connection
Equipment design	• Proven reliability • Compact	• Modular design	• Allows compact, modular equipment design • Reduced cabling and interconnection • Application-ready modules



Another application for IGCTs – in boiler feedpump drives **2**

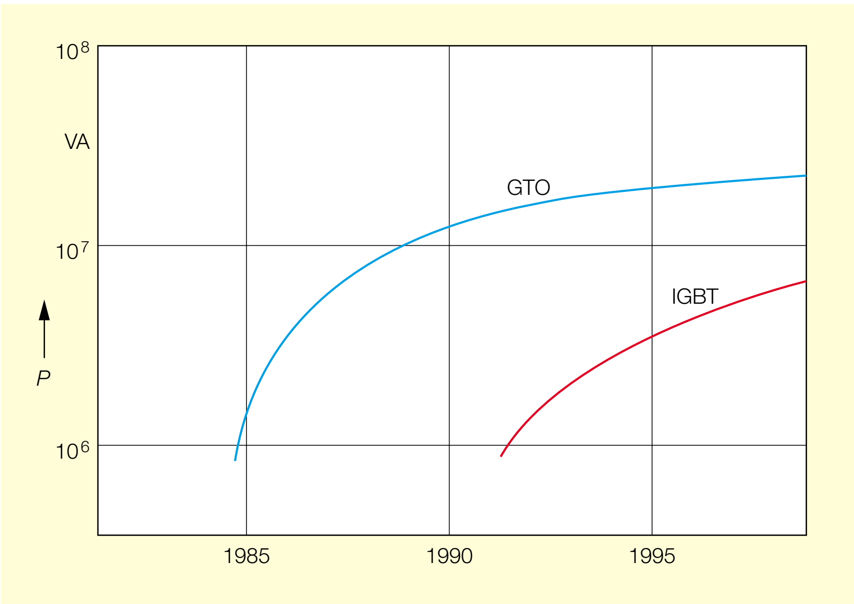
The combination of anode shorts and a buffer layer, however, leads to extremely high trigger and holding currents. To solve this problem the anode shorts have been omitted. Instead, the anode is made 'transparent', ie permeable, to the electrons, with the result that the trigger currents are reduced by almost one order of magnitude compared with a conventional GTO without buffer.

The second design innovation addresses the gate control. GTOs and thyristors are four-layer (npnp) devices. As such, they have only two stable points in their characteristics –'on' and 'off'. Every state in between is unstable and results in current filamentation. The inherent instability is worsened by processing imperfections. This has led to the widely accepted myth that a GTO cannot be operated without a snubber.

Essentially, the GTO has to be reduced to a stable pnp device (ie, a transistor) for the few critical microseconds during turn-off. To stop the cathode (n) from taking part in the process, the bias of the cathode n-p junction has to be reversed before voltage starts to build up at the main junction. This calls for commutation of the full load current from the cathode (n) to the gate (p) within about one microsecond. Thanks to a new low inductive housing design, 4,000 A/µs can be achieved with a low cost 20-V gate unit. Current filamentation is totally suppressed and the turn-off waveforms and safe operating area are identical to those of a transistor (eg, an IGBT). Also, GTOs can now switch instantly, without jitter, so that series connection is no longer a challenge.

Improvement in performance of the GTO thyristor and IGBT **3**

P Switching power



Fusion of power device and circuit design experience

The IGCT technology is the result of intense collaboration between device designers at ABB Semiconductors and power circuit designers at ABB Industrial Systems. In fact, it was the co-development of the power silicon, the packaging and the additional circuitry needed to make the power switch suitable for industrial applications that made the IGCT's unique combination of characteristics possible in the first place.

IGCT technology brings together the power handling device (GCT) and the device control circuitry (freewheeling diode and gate driver) in an integrated package **4**. By offering four levels of component packaging and integration **5**, **6b**, it permits simultaneous improvement in four interrelated areas: low switching and conduction losses at medium voltage, simplified circuitry for operating the power semiconductor, reduced power system costs, and enhanced reliability and availability. Also, by providing pre-engineered switch modules, IGCT technology enables medium-voltage equipment designers to develop their products faster.

Advantages of medium-voltage IGCT technology

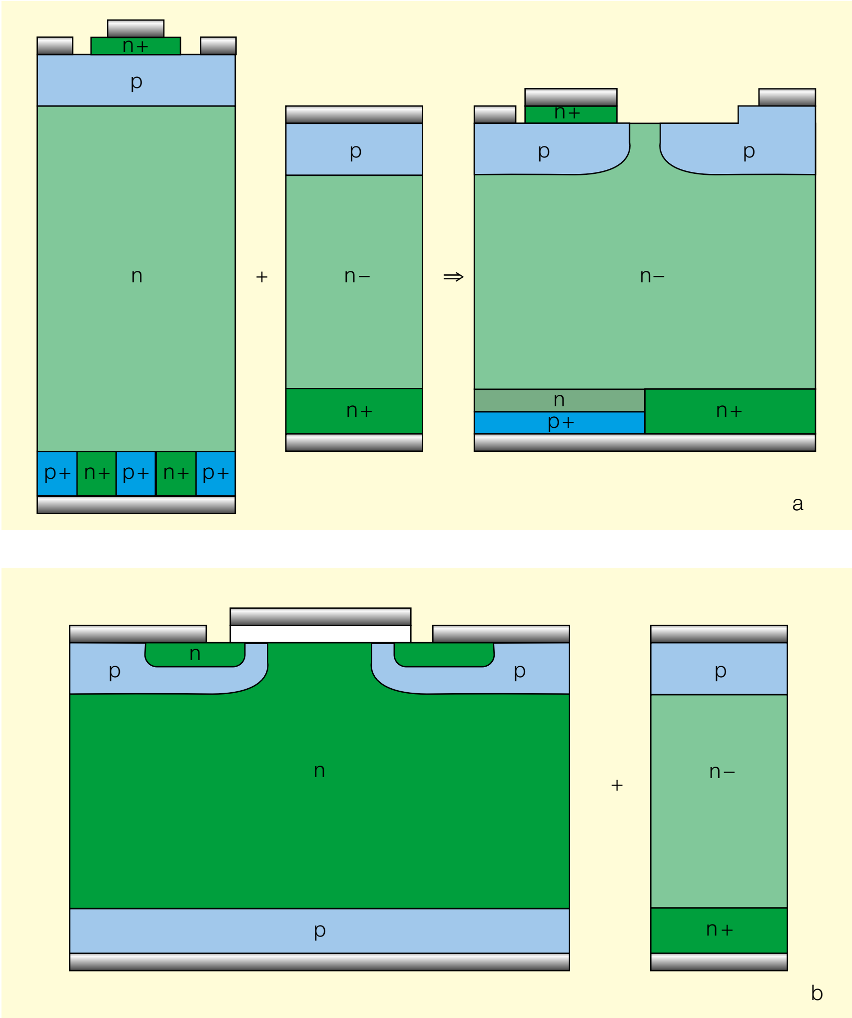
Low switching losses

An advantage of low-loss switching is that it allows equipment designers to choose the switching rate that best matches the end-application requirements. Previous power devices limited operation to 250 Hz at full rated current. IGCT technology can operate at up to four times that speed. In motor drive systems, for example, a designer might choose faster switching to obtain better system efficiency. Alternatively, the efficiency of inverter systems is improved and their losses reduced by selecting a slower switching rate for an IGCT.

Reduction of associated circuitry

The unique device-level characteristics of the GCT permit snubberless operation, with important benefits for design engineers. 6 demonstrates this clearly: inverter designs with snubbers are large and complex, while snubberless inverters, besides exhibiting lower losses, are compact and have far fewer components. Reliability is better as a result.

Equipment designs based on IGCT technology are also simplified by the integration of the freewheeling diodes in the GCT structure. This is possible as the reduction in thickness of the GCT silicon (the same reduction that makes low-loss switching possible) also permits an efficient diode to be fabricated on the same wafer.



Comparison of the GCT, with power switch and freewheeling diode integrated on the same wafer, and the IGBT. The GCT is significantly less complex than the IGBT. **4**

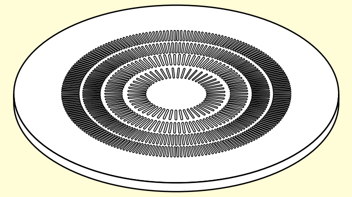
a *Cross-section through a GTO thyristor (left), diode (center) and GCT (right), showing how the transparent emitter and buffer layer of the GCT allows a thinner n-base layer. This permits integration of the freewheeling diode in the same structure, plus snubberless operation in combination with low inductive packaging and gate drive circuitry.*

b *Cross-section through a single cell of an IGBT (left) and a diode (right). A complete IGBT chip consists of many such monolithic cells in parallel. MOS technology limits the IGBT chip size to about 1–2 cm^2, so that several chips have to be packaged in parallel. As IGBTs have not yet reached the blocking voltage rating of GCTs, they have to be connected in series to obtain the blocking voltage for a particular application.*

Lower-cost power systems

The cost of power control equipment can be reduced by 30 percent or more through the use of IGCT technology. Several factors account for this.

GCTs can be fabricated using existing GTO production processes. Since these processes are well understood and available equipment can be used for them, GCT costs are in line with those of GTO thyristors. Compared with IGBTs, GCTs are less sensitive to process variations in terms of how these affect the turn-off performance. Consequently, the yield is higher and



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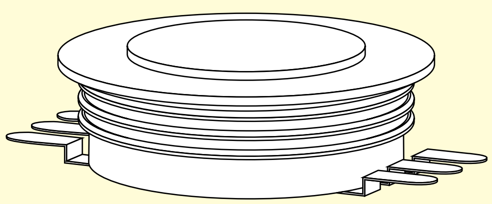

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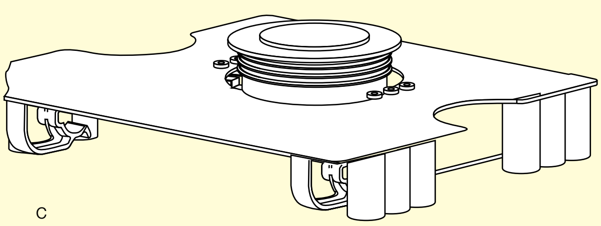


c

IGCT technology offers four levels of component packaging and integration (a, b and c, plus Fig. 6b). Equipment designers can select any level as the starting point of application development. When the application-ready IGCT stack (Fig. 6b) is chosen, much of the time-consuming work involved in designing the power circuit and mechanical systems can be avoided. **5**

a Gate commutated thyristor (GCT)
- *Gate commutated thyristor and diode integrated on same wafer.*
- *Anode design allows charge to flow in and out of device quickly.*
- *Reduced silicon thickness limits stored charge and permits fabrication of diode and switch on same wafer.*
- *Thinner silicon produces lower on-state losses.*
- *All elements switch at once; snubber can be omitted.*

b Packaged GCT
- *Low inductive housing permits charge and gate control currents to flow in and out of GCT quickly.*
- *Press-pack allows freedom of movement, preventing fatigue failures during decades of thermal cycling.*
- *Press-pack design withstands thermal stresses; contributes proven reliability.*

c Integrated gate driver (not to scale)
- *Low inductive gate drive circuitry permits control currents to flow in and out of GCT quickly.*
- *Localized, highly integrated gate drive circuitry reduces stray inductance.*
- *Compact size simplifies equipment design.*

costs are lower. In addition, GCT design simulation is simpler, reducing costs and speeding up system development.

GCT technology simplifies power circuits to the extent that the number of components is reduced by as much as 50 percent. This is due to the integration of the diodes in the GCT and the reduction in cabling and interconnection made possible by the generally high level of integration. A further reduction in costs is possible due to the higher operating frequency, which allows some components to be made smaller. In addition, the gate drive circuit power is substantially reduced, allowing less costly components to be employed.

IGCT-based equipment can be designed with higher efficiencies than when other technologies are used. Losses in the power circuits and in the associated circuitry are lower, translating into more compact cooling equipment for a further reduction in costs.

Reliability and availability

In a larger context, the cost of power control equipment is small in comparison with the cost of downtime of the process in which it operates. Equipment availability is therefore paramount. IGCT technology was conceived specifically for use at medium-voltage levels and ensures optimum equipment reliability through:

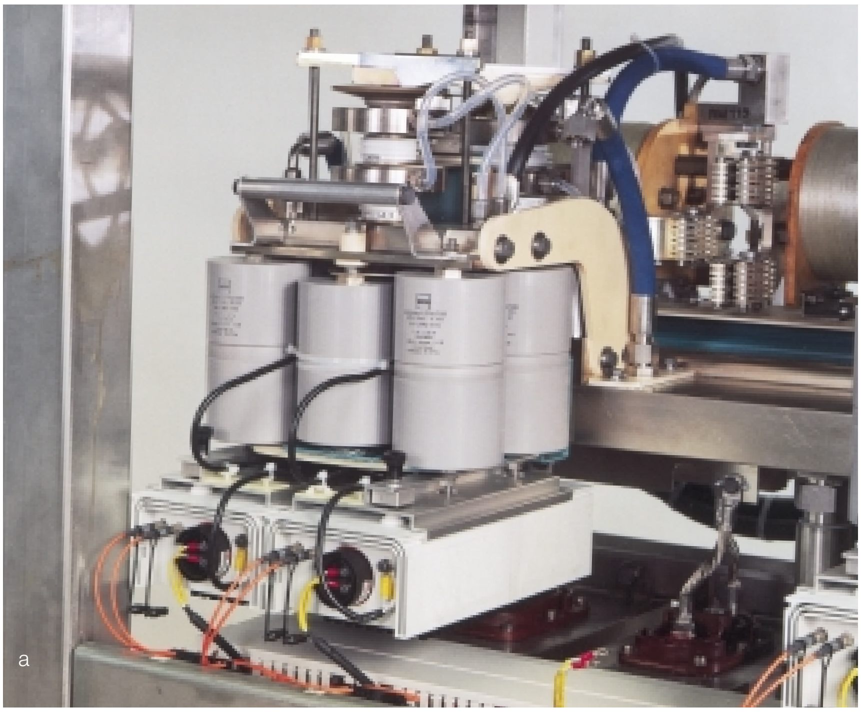
- Homogeneous switching
- Robust, thyristor-like packaging technology (no wire bonds)
- Simplified gate control units
- Reduced number of parts

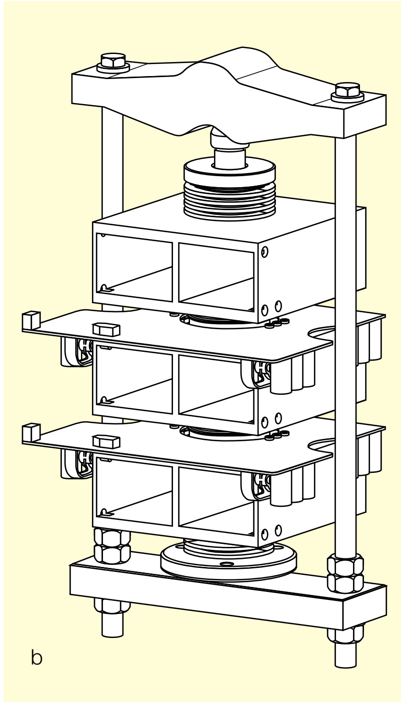
Further, in the unlikely event of a failure, the modular nature of IGCT technology makes replacement of power components quick and simple. This reduces spare-parts costs and keeps processes on-line.

Applications of IGCT technology

At the core of the IGCT's performance advantage is its ability to turn off in 2 microseconds and conduct like a thyristor. IGCT technology therefore permits simple inverter designs with half the losses of alternative technologies. Thanks to IGCTs, previously impractical circuit topologies rated at up to 100 MW and requiring series connection of many devices can now be realized. Medium-voltage equipment based on this technology exhibits very high reliability.

For the first time, a power silicon technology has been matched to medium-voltage, high-power applications. This enables equipment designers working





Comparison of GTO thyristor converter and IGCT converter for the same power and voltage levels. IGCT technology allows a dramatic simplification that translates into lower costs and improved reliability. **6**

a *GTO thyristor converter*

b *IGCT converter, air-cooled (air-coolers are shown simplified), with following features:*
– IGCT elements easily mounted in compact configuration
– Design permits fast replacement of IGCTs in unlikely event of failure

with IGCTs to build less costly, more reliable and more compact power control systems, including:

- Railway power supply frequency changers
- Utility interties
- Static var compensators for power factor control **1**
- Power flow controllers for utilities
- Medium-voltage drives with line voltages of up to 6.9 kV rms
- Pump and fan drives for the chemical, oil and power sectors **2**
- Marine drives/all-electric ships
- Transformerless traction supplies
- Locomotive drives
- Induction heating resonant inverters
- Static breakers

IGCT technology is available now

ABB is a leading supplier of high-power switching devices to ABB Group companies and external firms. This leadership is exemplified by the innovations that have produced IGCT technology. IGCT-based equipment benefits from lower costs and high reliability even at the highest power levels. Designers of medium-voltage equipment can now choose from three power silicon switch technologies: GTO thyristors, IGBTs and IGCTs. IGCT technology will be the technology of choice for all applications in which the priorities are compactness, high efficiency, fast development and proven reliability.

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