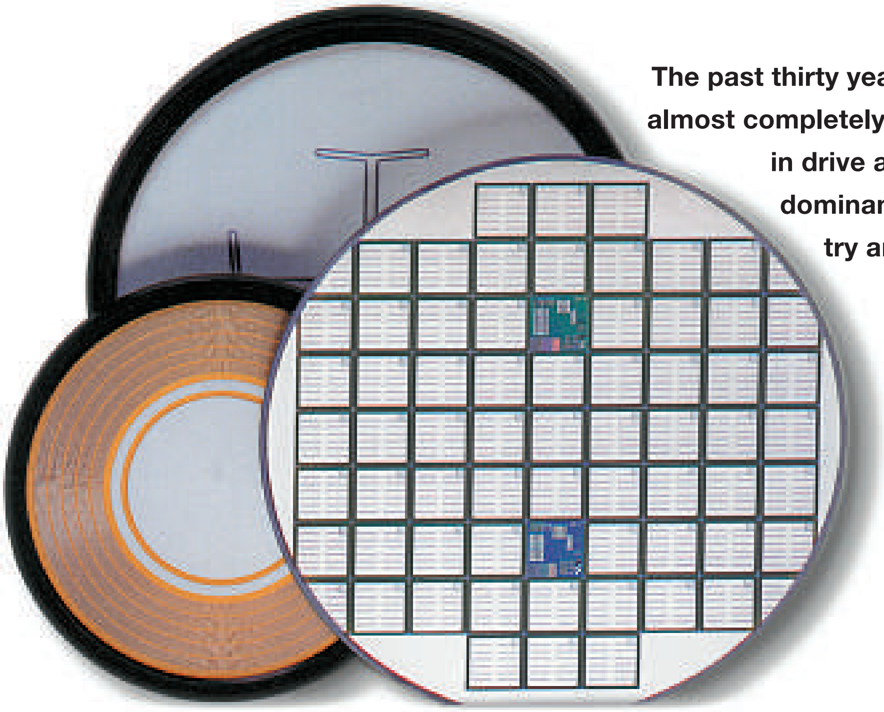
Power semiconductors

At the center of a silent revolution

Stefan Linder



The past thirty years have seen power semiconductors almost completely replace electromechanical solutions in drive applications and power supplies. This dominance is easily explained: Across industry and in transportation, as well as in energy transmission and distribution, power semiconductors offer users almost unlimited freedom in shaping the flow of electrical energy.

But what is it about power semiconductors that make them so overwhelmingly superior for high-power applications? Time to take a look at another ABB success story.

Explaining how power semiconductor devices function couldn't be easier – like a simple switch, they know just two states: 'open' and 'closed'. However, unlike simple switches they are able to 'flip' between these two states very quickly, usually in just a few microseconds. So by using fast on/off pulses, virtually any desirable shape of energy flow, such as the sine-wave in 1, can be produced.

Power semiconductor switches can be built with a wide range of voltage and current ratings, tailored exactly to the needs of industrial users. Nowadays, the maximum blocking voltage lies in the region of 6500 to 8500 V, while the maximum conduction current of a device can be anything up to several thousand amperes. For higher ratings the power semiconductor switches can be connected either in parallel or series. This is the case, for example, in high-voltage direct current (HVDC) transmission, where voltages up to 600 kV are used.

Losses – small, but meaningful

Three types of semiconductor device have established themselves in the high-power segment: thyristors, IGCTs (integrated gate commutated thyristors) and IGBTs (insulated gate bipolar transistors) 2, 3. Although their dominance implies ideal devices, this is by no means the case – they generate losses. While these losses are relatively small – typically less than 0.5% of the switched energy is dissipated as heat – the amount of energy they handle is large, so the real loss is substantial. Removing the produced heat can be complex, and is a major cost factor in system design.

The root cause of these losses lies in the physics of the devices: In the 'off' state hardly any mobile electrons exist in the silicon body of the element, so no current can flow. When the device turns on, the silicon body is literally flooded with mobile electrons, making the switch a good conductor of high current. However, the mobile charge carrier concentration in the on-state is still not as high as in, say, a metal. As a consequence, there is a noticeable voltage drop. The losses associated with this are called *conduction losses.*

When the switch returns to the insulating state, all the previously introduced electrons have to be removed again from the silicon body: This is done by the returning voltage, which 'sweeps' them out. Thus, at turn-off, current flows for a short moment at a high voltage, producing so-called *turn-off losses.*

The 'old economy': the thyristor

The thyristor is the oldest of the switching devices in use nowadays and still enjoys wide commercial success. Unlike the newer IGBT and IGCT, however, it can only be turned on, and not off. The thyristor returns to its off-state only when the load current reverses its direction. In practice, this is accomplished through an external, so-called *forced commutation circuit*, or via natural current commutation, for instance when the sine wave crosses the current zero. Forced commutation is no longer used in new system designs now that IGBTs and IGCTs are available. These can be conveniently turned off via gate signals, so there is no need for expensive external circuits. The reason the thyristor still exists alongside these more advanced gated turn-off devices is that its conduction losses are much lower. This makes it ideally suited for systems with high currents and natural commutation – like HVDC. In fact, the thyristor still is the preferred device for HVDC systems with power ratings beyond 500 MW.

> The thyristor, although it can only be turned on and not off, exhibits low conduction losses, making it ideal for systems with high currents and natural commutation – like HVDC.

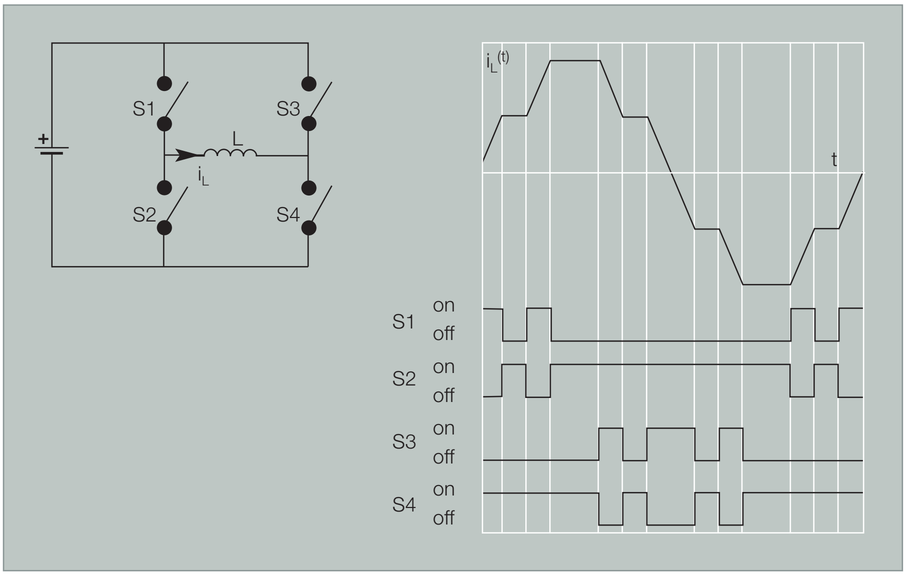
'New economy 1': the IGCT

In contrast to the classic thyristor, the integrated gate commutated thyristor, or IGCT, can be gated on and off whenever required, making it a 'true' switch. Unfortunately, this new freedom comes at a price: the voltage drop in the conducting state is larger than with the thyristor.

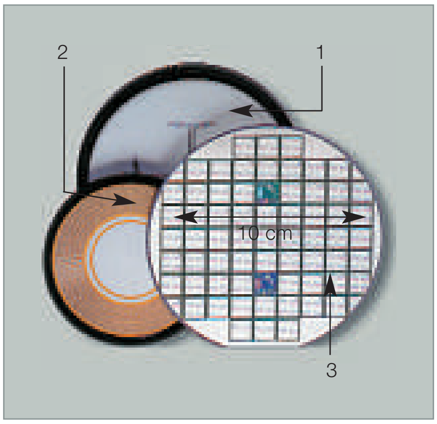
The IGCT is controlled by current signals at the gate electrode. The control power depends heavily on the switched current and on the pulse rate, and is typically of the order of 10 to 50 watts.

Due to the physics of the IGCT, it is impossible to influence the transitions between the on- and off-state. Once the gate signal has been given, there is no way back – the device will switch and

1 Four simple on/off switches and a battery are all that is needed to generate an approximately sinusoidal current in an inductor (L).



2 Three types of semiconductor device have established themselves in the high-power segment.



1 Thyristor element used in HVDC transmission
2 IGCT element for applications rated 2–5 MW
3 Silicon wafer with approx 50 IGBT 'chips' each able to switch about 200 kW.

can only be governed by its internal dynamics. In practice, this has several important consequences:

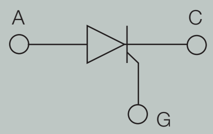
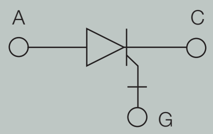
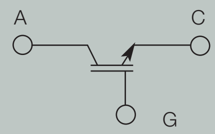
- The IGCT produces steep current transients (di/dt) at turn-on that can destroy auxiliary elements, especially diodes (rectifying devices, the electric equivalent of one-way valves). Because of this, a turn-on protection circuit – the so-called *di/dt snubber* – is connected in series with the IGCT to limit the maximum rate of current rise.
- IGCTs can only be connected in parallel when a second protective circuit – a *dv/dt snubber* (essentially an RC element) – is also connected in parallel with them. To avoid having to include this snubber, the turn-off timing would have to be very precisely synchronized (on the nanosecond scale), something which is not feasible at the moment.
- If the application calls for many IGCTs connected in series, it will be necessary to compensate for all internal and external tolerances able to cause a mismatch in the turn-off timing. This again requires a dv/dt snubber. Its capacitor absorbs all the charge differences arising from the minute turn-off time differences, thereby sharing the voltage equally between the devices.

Armed with this information, it is easy to see where the IGCT offers most benefits: in high-power applications where neither parallel nor series connection is needed or desired. Medium-voltage drives rated above 500 kW, for example, can be made very compact and will exhibit low losses when IGCTs are used.

The benefits of the IGCT come to bear in high-power applications where neither parallel nor series connection is needed – as in MV drives rated above 500 kW.

It remains to be mentioned that the IGCT evolved from the gate turn-off thyristor, or GTO. Widely used prior to the introduction of the IGCT, the GTO is hardly used today in new system designs.

3 Key properties of the thyristor, IGCT and IGBT

Element	Thyristor	IGCT	IGBT
Symbol			
	A = Anode; C = Cathode; G = Gate (control terminal)		
Control	On: current pulse at G Off: reverse current through A–C	On/off through current signals at G	Variable resistor, controlled through G–C voltage
Parallel connection	Parameter matching (selection of devices)	Requires protective circuit	Possible without protective circuit
Series connection	Requires protective circuits		Protective circuits optional (recommended)
Short circuit & fault protection	Elements do not limit short-circuit current; protective circuits required		Element limits short-circuit current; short circuit may be shut off via G signal

'New economy 2': the IGBT

The insulated gate bipolar transistor, like all transistors, but fundamentally unlike thyristors, is a linear element and can therefore be controlled at all times. Through this controllability, the transitions between the on- and off-states can be slowed down dramatically, making the IGBT a very user-friendly device:

- None of the protective circuits required by the IGCT are needed.
- The IGBT can be connected in parallel without any serious difficulties.
- Series-connection is possible without dv/dt snubbers. However, for optimization purposes it is still advisable to connect a small RC filter in parallel with each device.

Besides being user-friendly, the IGBT has two further important advantages:

- It is controlled via voltage signals applied to so-called MOS (metal oxide semiconductor) inputs. Hence, the required control power is very low, with 1 to 2 watts usually being sufficient. This is a key benefit for series connections, as in HVDC circuits, since supplying the gate control circuit with the required power is technically complex, and therefore expensive for high-voltage systems.
- In the event of a short circuit through it, eg due to failure of a motor winding, the IGBT automatically limits the short-circuit current to between 5 and 10 times the rated current. The short circuit can then be safely cleared within 10 microseconds using just a normal IGBT turn-off signal. No damage is caused to the device as a result of such short circuits.

The only price that has to be paid for all these benefits is a somewhat lower mobile charge carrier density during conduction than with the IGCT, causing the IGBT's conduction losses to be higher. However, as fewer carriers have to be swept out at turn-off, the turn-off losses are lower.

The IGBT's flexibility and easy handling predestine it for a wide range of applications in energy transmission and distribution. A good example is ABB's HVDC Light™ technology [1].

The right package for the right job

The power semiconductor housing is of paramount importance for the targeted field of application. Two different types are available, the preferred one being chosen on the basis of three main criteria:

- The method used to transfer the heat from the semiconductor to the heat sink.
- The method used to insulate the power terminals from the heat sink(s).
- The semiconductor's failure mode.

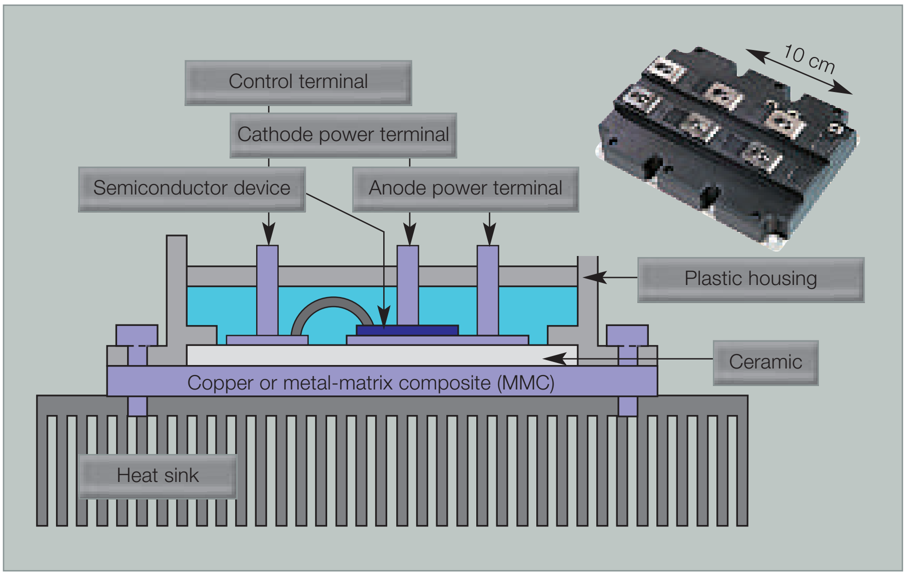
Flexible: The insulated housing

The main design feature of the insulated housing is an electrically insulating but thermally highly conductive ceramic plate that separates the thermal and electrical functions. The housing is placed over this plate, to which the semiconductor components are attached, and then bolted, face down, onto a heat sink 4. Thanks to this galvanic separation, multiple components at different electrical potentials can be mounted on just one heat sink. The heat sink itself can be at a defined (eg, ground) potential. System building blocks – for example, an entire inverter – can be integrated inside a single housing of this type.

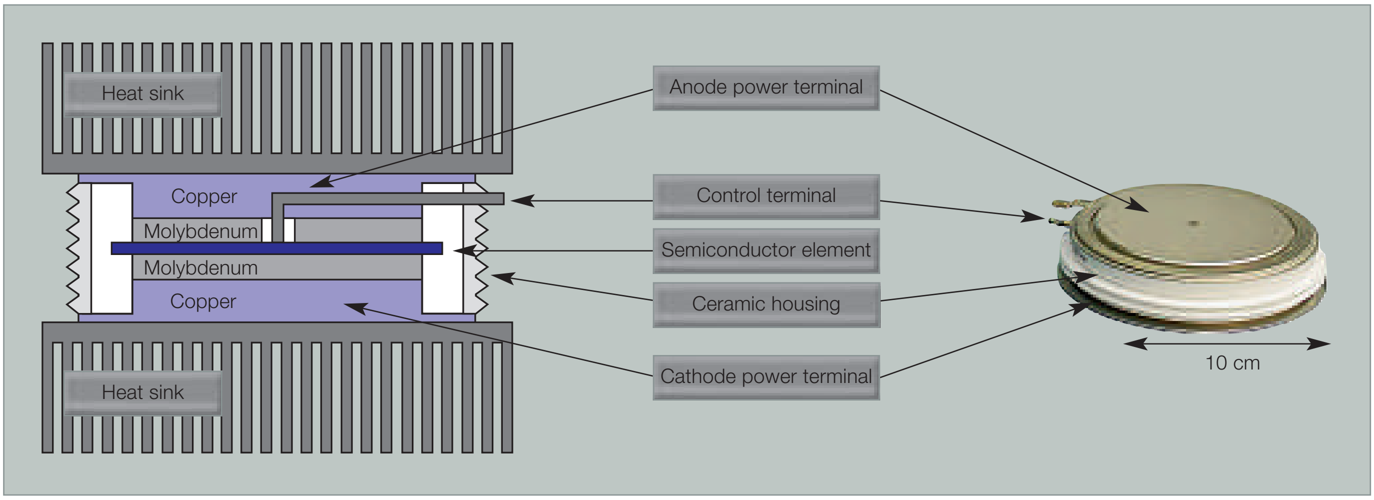
The insulated housing is today the standard packaging method for IGBT products, being generally referred to as an *IGBT module* on account of the fact that it usually accommodates several semiconductor chips. Among the IGBT products manufactured by ABB in insulated housings is the *LoPak*™ module with maximum blocking voltages of 1200 V and 1700 V and current ratings from 50 A to 900 A. The modules are configurable as a single-phase leg (two switches in series, with mid-point tapping) or as a three-phase, full-bridge inverter. The *HiPak*™ series is configured as a single switch with ratings from 1200 V / 3600 A over the voltage classes 1700 V, 2500 V, 3300 V, up to 6500 V / 600 A.

Insulated housings are preferred for applications with power ratings up to a few megawatts. Systems with higher ratings, as in HVDC transmission, usually require series-connected components. However, the insulated housing has some drawbacks that make it unsuitable for series connection:

4 Insulated housing. Since the heat sink is galvanically insulated from all the power terminals, multiple components can be mounted on one common sink.



5 Press-pack housing. The heat sinks are at the electrical potential of the anode and cathode. Molybdenum disks act as 'strain buffers', reducing any mechanical wear that might occur during temperature changes.



- The insulation capability of the ceramics is limited to just a few kV; series connection on a common heat sink is thus only possible with relatively low voltages.
- To increase the availability of HVDC and other high-voltage systems, redundant devices are added. If one of the series-connected devices fails, the remaining switches keep the valve functioning, but only if the failed device assumes a low-impedance state (ie, it is 'shorted'). However, the construction of the insulated housing usually causes the device to fail in the 'open' state.

To be able to exploit the advantages of IGBT technology in HVDC transmission and other high-voltage and high-power applications, such as reactive power compensation or flicker control, ABB therefore developed a unique press-pack housing for the IGBT.

Powerful: The press-pack housing

This type of housing has no ceramic plate and the thermal and electrical functions are not separated 5. Instead, it is pressure-contacted, ie an external high-force clamping mechanism presses the housing with its electrical terminals onto two heat sinks. The load current thus flows 'vertically' through the device as well as through the heat sinks. Pressure-contacted housings can be connected in series simply by stacking them on top of each other, with only their heat sinks between them. Another advantage lies in their failure mode: when the semiconductor fails, the high pressure causes the metallic anode and cathode pole pieces to fuse and form a reliable low-impedance path (ie, a short-circuit). These two characteristics make the press-pack housing the ideal package solution for all high-voltage and high-power applications.

> ABB's IGBT press-pack housing is designed for simplified clamping and assembly, plus easy adaptation to customers' needs.

Pressure-contacted housings are the standard package for ABB thyristors, GTOs and IGCTs. Thyristors are available with a wide range of currents and voltage ratings up to 8500 V. IGCTs can be supplied in different configurations for maximum blocking voltages from 4500 to 6500 V.

ABB's IGBT press-pack housing deserves special mention. Built to meet the most rigorous demands, its unique proprietary construction makes the product virtually immune to non-uniform pressure distribution in clamping. This allows a greatly simplified clamping construction and assembly procedure, as well as much higher field reliability, for very significant cost savings. Due to its modular design, ABB can easily adapt the current rating of the product to customers' needs. ABB offers the IGBT press-pack housing under the trade name *StakPak*™ 6. This product is also at the heart of ABB's HVDC Light™ technology.

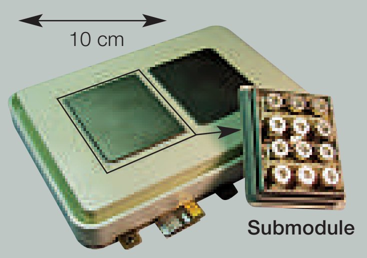
Getting better all the time

Power semiconductor technology today exploits almost the full potential of silicon, so quantum leaps may no longer be expected. Also, components with much higher voltage ratings (above 10 kV) are technically very difficult to realize.

To overcome these barriers, research institutes all over the world are running programs aimed at finding new materials with improved properties. The currently most prominent of these is silicon carbide (SiC). Unfortunately, these new materials pose some serious technological difficulties which are proving hard to resolve. From today's standpoint, it seems unlikely that they will become a viable alternative to silicon in the power regime above 100 kW within the next 10 to 15 years.

What can be expected in the meantime is the continuous improvement of today's components: lower losses, higher currents, and better switching behavior. Significant progress in the housing technology can also be expected. The devices will become more user-friendly, while new materials will allow improved cooling for even better utilization of the semiconductor's full potential.

6 *StakPak*™, ABB's proprietary IGBT press-pack housing concept



Up to six submodules are possible, each with a switching capacity of 600 to 1000 kW.

Stefan Linder
ABB Power Technologies
CH-5600 Lenzburg
Switzerland
stefan.linder@ch.abb.com

References

[1] **G. Asplund, et al:** HVDC Light – DC transmission based on voltage sourced converters. ABB Review 1/1998, 4–9.

For more information, visit www.abb.com/semiconductors.