Electronics with POWER

Power semiconductors for transmission and distribution

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Power electronics solutions are replacing traditional electromagnetic systems in T&D applications at an ever-faster rate as utilities increasingly recognize the need to improve the efficiency and functionality of existing infrastructure. A bonus of this new functionality is that it facilitates the connection of small-scale distributed generation units and renewable energy sources to individual consumers and to the power grid. In addition, the new electronics-based technologies are making it possible to massively reduce the size of the electricity infrastructure, thus minimizing its environmental and visual impact and freeing valuable space and resources for other uses.

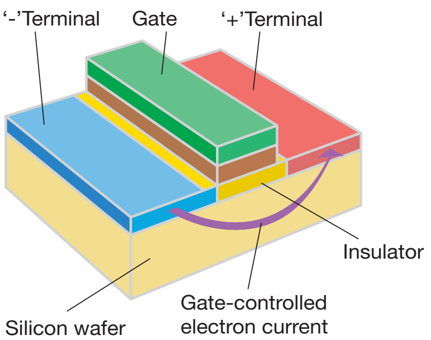
The T&D industry is currently going through a transitional phase with far-reaching consequences for electric utilities and the public sector alike. With its reliance on new power semiconductor devices appearing on the market at an increasing rate, this transition is being driven to a large extent by heavy investment and intensive development activity in both the information technology (IT) and the microelectronics sector.

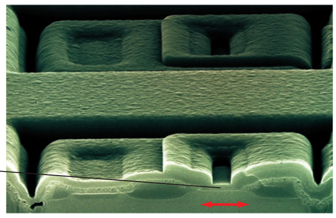
These new generations of power semiconductors offer improved performance, higher reliability and excellent controllability. In addition, intensive research into new materials, such as silicon carbide, has been encouraging and shows potential that goes beyond the limits of the present 'workhorse' material – silicon.

New forces driving electrical engineering

Still developing at an extraordinary rate, the IT industry has become one of the largest industries in today's world economy. A characteristic of this industry, and one which also helps explain its phenomenal growth, is extremely high investment in R&D. The spectacular developments in software and microelectronics technologies that this has led to have also become key driving forces in

1 Left: MOS transistor – the 'workhorse' of microelectronics. Right: Cross-section through a silicon wafer, showing the features making up the MOS device





'knock-on' applications, eg in electrical engineering.

The MOS-transistor (Metal Oxide Semiconductor) 1 is one of the cornerstones of state-of-the-art microelectronics. This device makes it possible to control, with high precision, a current in a semiconductor by applying a voltage to an insulated gate electrode. What is more, the power required to do this is extremely low. The MOS-transistor lends itself to very cost-efficient manufacturing, all the small features building up the transistor function being created in a planar process using photolithographic methods similar to those used in the printing industry. Massive R&D investments in recent decades have resulted in a continuous reduction in the size of the individual elements on electronic circuits. (This is the basis for Moore's law 2, which states that the number of transistors that can be manufactured on one single semiconductor chip doubles every 18 months.) Today, more than 100 million transistors, each with an area smaller than 10^{-6} mm^2, can be manufactured on a single 1–2 cm^2 chip. In combination with advanced software, new, low-cost products with broad functionality and extreme efficiency are now 'taken for granted' in this field.

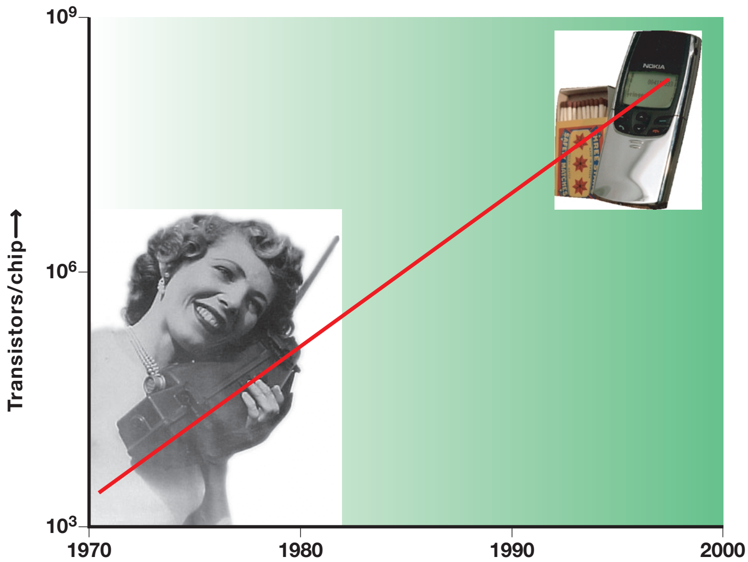
Handling high power – the traditional approach

Traditionally, the electronic conversion of electrical power in the high-power region has made use of the principle of line-commutated frequency conversion, with thyristors used to control the current flow. The thyristor is the equivalent of a 'binary current valve' with two discrete states, one conducting and one blocking the current. Turn-on is accomplished by injection of a gate current, with turn-off determined by the 50/60-Hz line voltage passing through zero. However, the fact that the thyristor cannot be turned off with the gate terminal limits the range of applications for this device. Having been used to handle high power for more than 40 years, thyristors are now available with impressive power-handling capabilities 3 and often represent a cost-efficient alternative at the highest power levels.

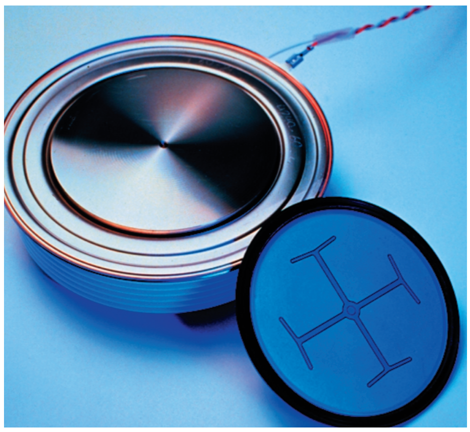
Elaborate gate control – boosting thyristor performance

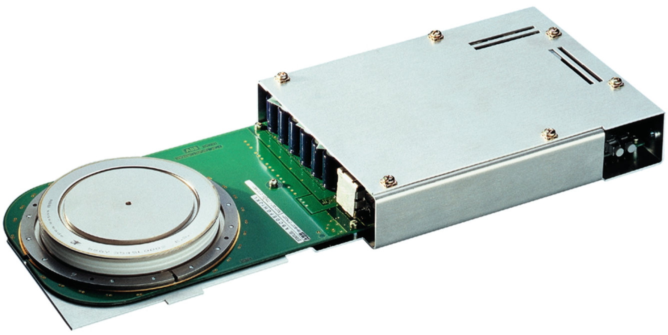
Gate-controlled turn-off was introduced in the late 1970s with the Gate Turn-Off

2 Moore's law – smarter, smaller. New technologies and efficient manufacturing are the main forces driving development of MOS-based semiconductor chips – the building blocks for today's IT products.

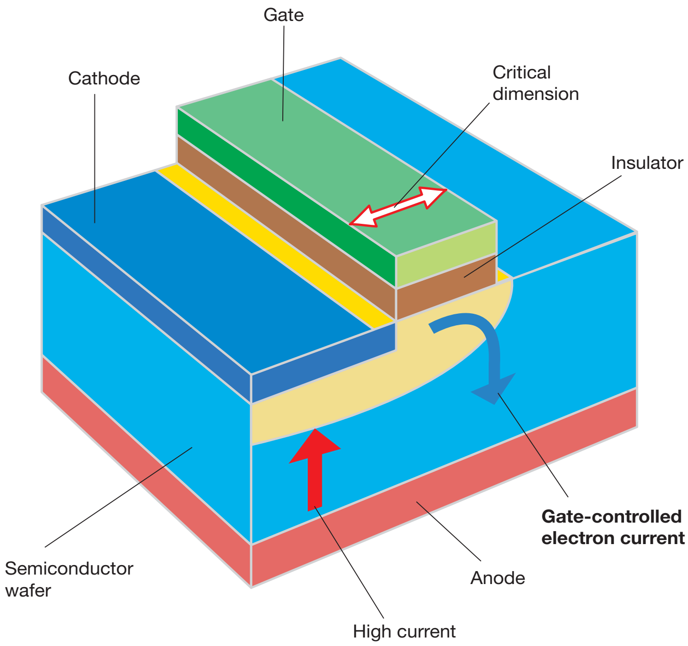


3 This high-power silicon thyristor, designed for HVDC transmission applications, can handle 8000 V and 2000 A. It utilizes a full 5-inch silicon wafer.





4 ABB's IGCT technology has raised the bar for thyristor performance and cost-efficiency.



5 The combination of high-impedance MOS surface transistors for efficient, low-power control, and a vertical transistor for high current and voltage capabilities, endows the IGBT with excellent controllability and very high power gain.

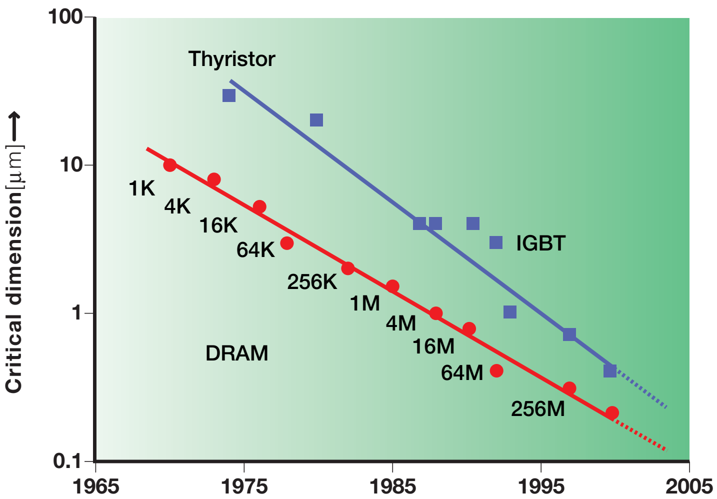
(GTO) thyristor. By making it possible to build efficient converters for controlling the output frequency, the GTO opened the door to variable-speed AC motor drives and other similar applications. However, power losses are higher with the GTO than with classical thyristors, and elaborate units for supplying the high gate currents became necessary, as well as 'snubber circuits' for individual device protection. A remarkable improvement in GTO thyristor performance came with the introduction by ABB in 1997 of a new device concept – the Integrated Gate Commutated Thyristor (IGCT) [1]. This new technology featured, for the first time, homogeneous and precisely controlled injection and extraction of gate currents in thyristors by means of an integrated gate drive unit 4. Using this concept, the freewheeling diode, which has to be connected in antiparallel with the switches in many types of converter, can be integrated on the same semiconductor wafer, simplifying the mechanical design of the converter. The homogeneous switching across the device area that occurs in the IGCT results in significantly lower losses than with the GTO [2]. The reduced demands made on the converter infrastructure, eg capacitors and filters, means that the size of the converter is also reduced.

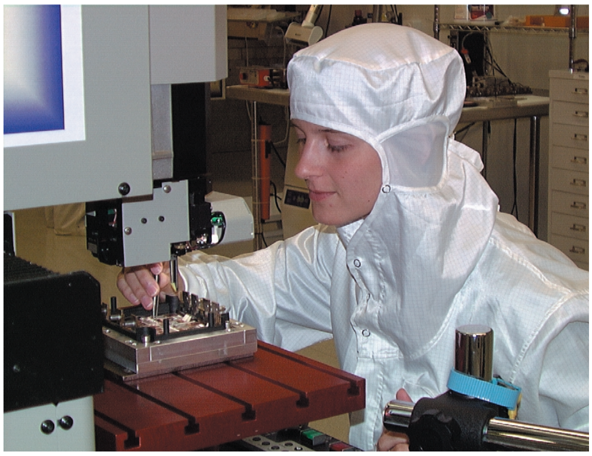
With its proven high reliability, the IGCT represents an optimal, cost-efficient choice for many high-power applications requiring turn-off devices. Typical uses at present include large drive systems and traction power supply systems [3].

Merging traditional power semiconductors with modern microelectronics

Numerous attempts have been made to combine the microelectronic technologies used for very precise control of the low-voltage signals in integrated circuits with the high power-handling capabilities needed for power semiconductor devices. The most successful to date has been the Insulated Gate Bipolar Transistor (IGBT) [4], which combines a high-impedance, low-power gate input with the power-handling capacity of normal bipolar transistors and thyristors.

Control of the IGBT is accomplished by means of a pattern of MOS transistors, distributed on the surface of the device 5. These MOS transistors allow high-impedance control of the current flow through the device, so that only an extremely low power has to be supplied to the control gate. The ability to sustain high voltages and currents is provided by the vertical part of the device, which comprises a bipolar transistor structure.





6 Thanks to the use of manufacturing technologies developed for ICs and memories, performance levels of the new power semiconductors are advancing along a similar curve.

7 Advanced semiconductor packaging techniques are key to ABB's leading position in power electronics.

The thickness of this vertical transistor is sufficient to withstand high voltages. The vertical transistor effect is also crucial as it enhances the conductivity of the semiconductor material, and hence reduces the voltage drop across the device during the conducting phase.

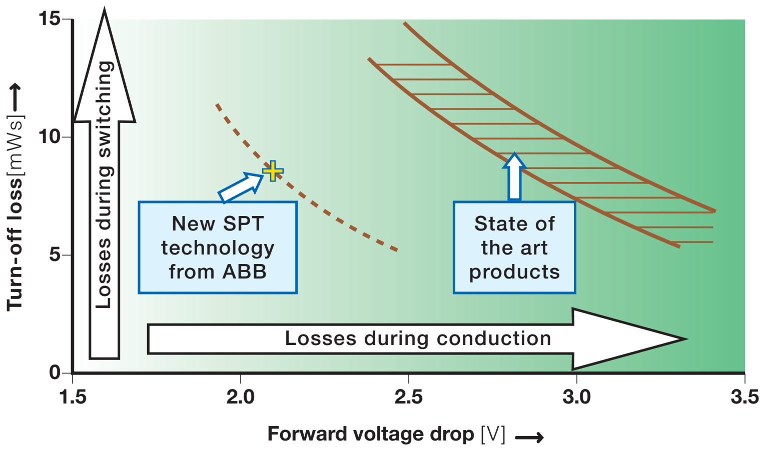
IGBT performance is related directly to the properties of the surface MOS transistor cells, and the success of these devices is largely due to the continuous development of the cell structures, in many cases using technologies that were developed for microelectronics circuits addressing substantially larger markets 6. Accurate control of the manufacturing process is vital to ensure uniformity and reproducibility, and so guarantee high performance and reliability for these devices.

Although the 1980s saw substantial progress made in the development and production of IGBTs for lower voltages (600-1200 V), it was not until the beginning of the 1990s that it was realized that the same concept could also be used for higher voltages [5].

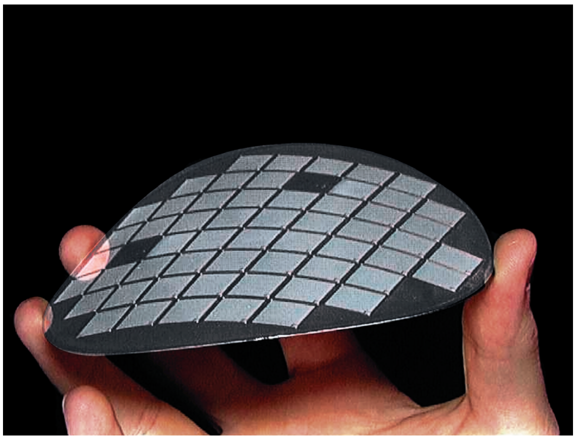
Since then ABB has extended its broad power semiconductor product portfolio to include IGBT power modules in the voltage range of 1200 V to 4500 V. Close cooperation with customers has made it possible to optimize these products for important applications 7.

With its new 1200-V IGBT product line based on the unique SPT (Soft Punch Through) technology [6], ABB has taken IGBT performance a step further 8. The MOS transistors on the surface of the wafers, like the silicon wafer thickness, are optimized for high performance when the IGBT is conducting current and for very low losses when the device switches to the off-state to prevent current flowing.

Since power semiconductor losses are, in a first approximation, proportional to the square of the device thickness, reducing this thickness is an obvious choice when considering what to optimize. With SPT, ABB has made a quantum leap, reducing the thickness of 1200-V IGBTs to less than 70% of the thickness of previous devices. Moreover, their planar cell structure, which facilitates reproducible and cost-effective manufacturing, endows the new 1200-V IGBT with low on-state losses comparable with the more complex, 'trench-based' IGBTs, which are optimal in this respect. In terms of turn-off capability, the new concept compares with so-called Non-Punch-Through (NPT) IGBTs, which have been optimized with regard to this parameter. In addition, SPT technology makes it possible to manufacture devices with an extremely 'soft' switching behavior, reducing problems with electrical noise in



8 Comparison of 1200-V IGBT performance. Data taken at 600 V, 75 A, 125°C.



9 Silicon wafer produced using ABB's latest IGBT technology. This 5-inch wafer is 125 µm thick and carries more than 10 million transistors.

converters. Being able to manufacture extremely thin silicon wafers is key to this performance, as it minimizes the silicon material in the current path and hence the electrical losses of the device 9.

The technology platforms supporting the SPT product family are now being utilized to enhance the performance of IGBTs designed for higher voltages. In doing so, the broad experience base with very high voltage thyristor devices that ABB has built up over many years is being transferred to the design of high-voltage IGBTs.

An important factor to consider when optimizing the performance of high-voltage devices is the impact of cosmic rays. Originating in deep space, these particles could lead to spontaneous device failures. A considerable amount of research has been undertaken at ABB in order to understand these effects and design devices with minimal sensitivity to such particles.

Another important factor for high-voltage designs is the power density during switching operations. For a given technology, the maximum controllable current is basically inversely proportional to the voltage that the device has to handle. Therefore, the rated current for a given chip size decreases rapidly with increasing voltage. Under short-circuit conditions, the power density inside IGBTs easily reaches several MW/cm^2. This results in extremely fast heating of the IGBT, and even has the potential to destroy the device.

A major research effort is therefore being made at ABB to raise the destruction threshold, both with regard to the power density and the maximum energy absorption under extreme short-circuit conditions. The new IGBT technologies from ABB exhibit significantly improved performance in these two areas. Using 100% self-alignment techniques, it is ensured that the geometrical definition of all the features critical for manufacturing does not depend on the photolithography alignment quality. This results in extremely high uniformity, eliminating weak spots which could limit device performance. A special doping layer in the cells enhances the conductivity of the 'hole' current path. The effect of this is a considerable increase in the current density of the device (better area utilization) as well as a higher temperature limit (obtained by preventing latching of the parasitic thyristor). Furthermore, since the gate layer is optimized for minimum impedance, the gate signal propagation delay is also minimized. This ensures that the entire IGBT switches uniformly, increasing turn-off performance.

Another benefit of these new cell technologies is that a 'thyristor-like' plasma distribution is generated within the device. As a result, on-state conduction loss will no longer be so critical as a limiting factor for the maximum operating voltage of IGBTs, making them realistic alternatives to thyristors, GTOs and IGCTs in many applications. 6500-V IGBT samples are currently under test.

High-voltage IGBT power modules from ABB are currently being used in traction vehicles and for power transmission applications.

Table 1

Critical material properties of silicon (Si) and silicon carbide (4H-SiC). The data for diamond – the semiconductor material with the highest inherent potential for high-power devices – are shown for comparison.

		Si	*4H-SiC*	*Diamond*
Bandgap	eV	1.1	3	5
Breakdown field	MV/cm	0.3	3	10
Max electron velocity	10^7 cm/s	1.0	2	3
Thermal conductivity	W/cmK	1.5	5	20

Table 2: A promising future

Technical potential of SiC power devices, compared with the limits of silicon

- Device voltage — 5 to 10 times higher
- Current densities — 10 to 100 times higher
- Switching losses — 1/10th to 1/100th of today's
- Working temperatures — up to 500°C

Beyond silicon

Although the performance of power semiconductors based on silicon will continue to improve, fundamental limitations inherent in this material are within sight. Maximum power-handling density (robustness) and thermal stability (losses, cooling) are important device performance parameters that will be limited by such basic material properties. Silicon high-power diodes are already approaching these limits, and similar trends can also be made out for the semiconductor switches. Most converter designs require additional circuitry or are slowed down during switching [2] for device protection, increasing both costs and power losses. On the other hand, converters capable of much higher switching frequencies would be an attractive option for the high (>10 MW) power levels in typical transmission and distribution applications. Being able to operate the converter at high frequencies with low power losses would make it possible to minimize the size and cost of filters and cooling equipment

Such applications require solutions that go beyond changed device structures or new gate drives. One very promising alternative is to build devices based on silicon carbide (SiC). Due to the high atomic binding energy (bandgap) and high specific electric field strength (*Table 1*) of this semiconductor material, optimized devices made of SiC potentially offer one to two decades of performance improvement when compared with silicon-based devices (*Table 2*). Also, as SiC can be operated at considerably higher temperatures than silicon, it is possible for the power semiconductor to be integrated directly in electrical equipment such as generators and motors.

Commercial silicon carbide Schottky diodes for low-voltage applications (600 V), intended primarily for use in power supply products and power factor correction circuits, are now coming onto the market.

10 ABB has developed a process for manufacturing thick (30-60 µm) high-performance SiC epitaxial layers that makes use of a so-called hot wall chemical vapor deposition reactor. This unique process enables SiC power devices to be produced for the 5-15 kV range.

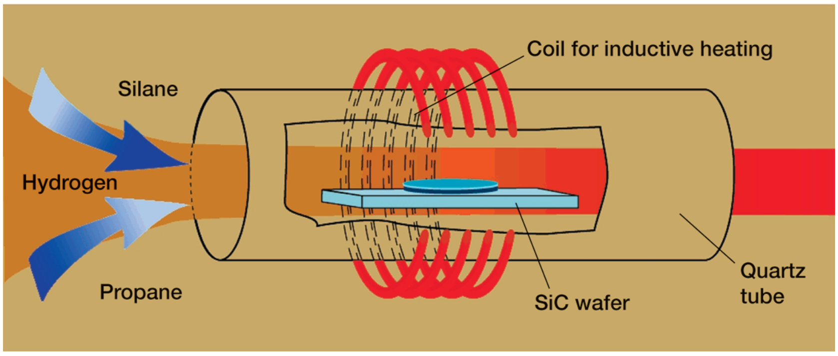
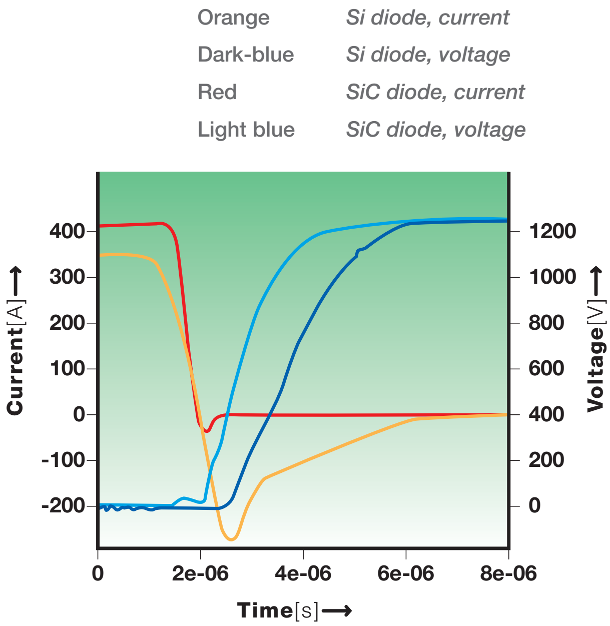


ABB committed to developing silicon carbide power devices some five years ago. Among other things, it has developed a proprietary process for the manufacture of high-quality silicon carbide material with the properties needed for high-voltage devices **10**. Diodes and switching devices are being processed in a new pilot plant, using manufacturing technologies developed specifically to handle this chemically tough semiconductor material.

It has been recently demonstrated that SiC power diodes for 2.5 to 4.5 kV and a 400-A switching current perform significantly better than comparable silicon devices [7]. The semiconductor switching losses for this type of diode are virtually eliminated **11**. As a first step, silicon IGBTs can be combined with these SiC power diodes to form hybrid modules. Using presspack techniques known from the silicon devices, power loss savings of 40-60% have been measured with this hybrid device in typical hard-switched converter configurations. 'All-SiC' power modules, including switching devices made of silicon carbide, have the potential to reduce the total converter losses to as little as 10-20% of the figure usual with today's technology.

This progress in semiconductor performance is closely linked to trends in the applications area. Traditionally, variable-speed motor drives and HVDC have driven high-power semiconductor

11 ABB has pioneered SiC R&D for HV devices with extremely low losses. This 2500-V/400-A module generates only 4% of the device switching losses produced by its silicon equivalent.

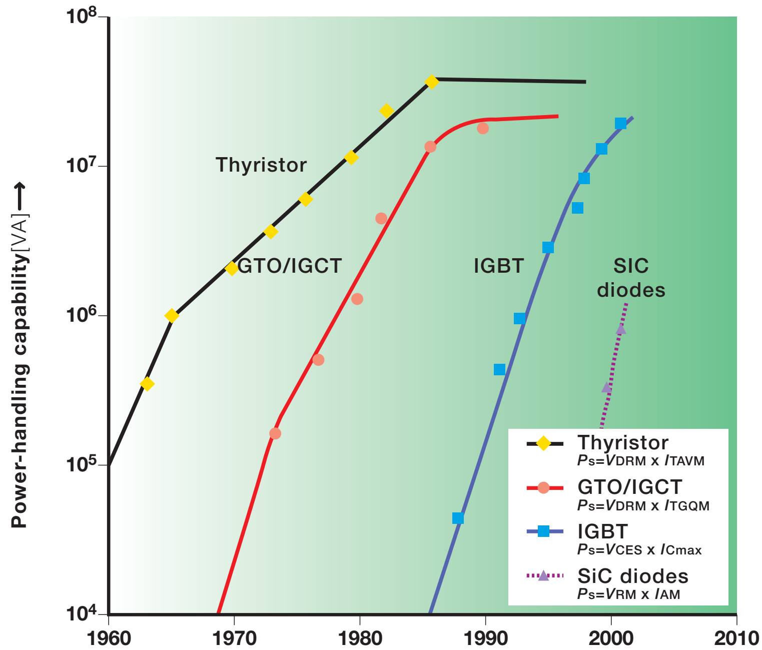


development. For high-power switching, systems with classical silicon devices operating at typical frequencies of 50-500 Hz are being replaced by converters using IGBTs that switch at 1-5 kHz. The new materials will continue to support this trend 12, fundamentally changing how and where power semiconductors are chosen for controlling power flow.

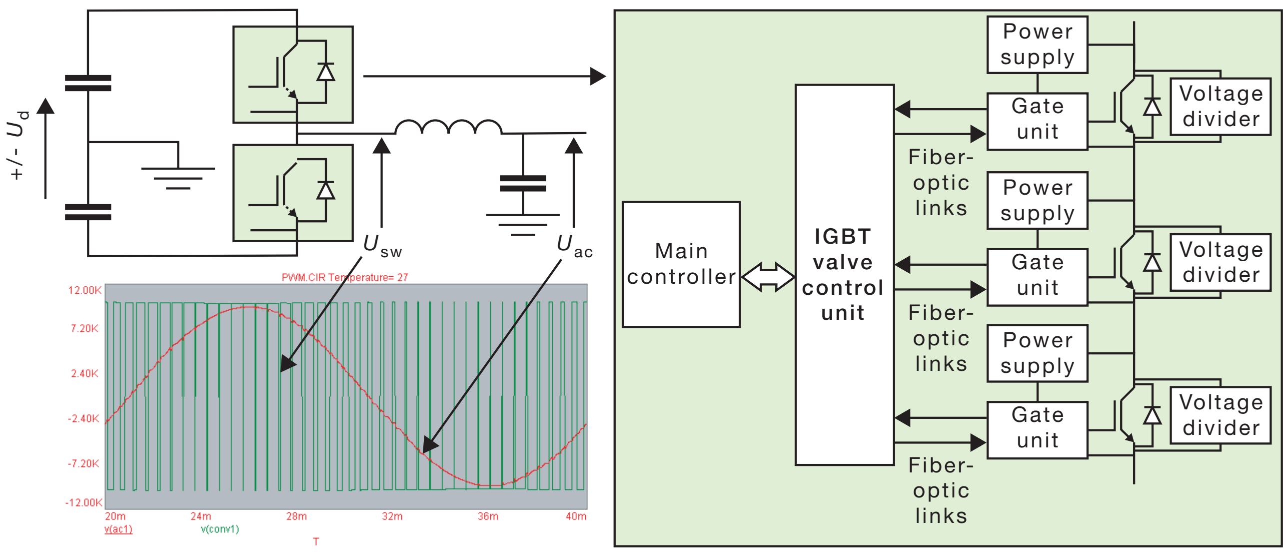
System integration

In transmission and distribution installations based on power electronics, it is essential to be able to optimize the different aspects of power semiconductor performance to meet the specifications for the total system. ABB's new HVDC Light system [8,9] introduces the concept of voltage source converters to transmission applications 13. The result is a new concept for DC transmission systems

12 Historical development of the power-handling capability of power semiconductors



13 PWM control of IGBT modules, connected in series, enables very compact DC transmission installations to be built.



14 Factory-assembled, pre-tested 'stacks' of series-connected IGBTs ensure high quality and minimize commissioning time.

that combines high functionality – and even improves the existing AC system – with a very compact design.

The IGBT modules for HVDC Light were developed as integral parts of the concept, both with regard to their electrical performance (*I* and *V* capability) and their mechanical and thermal properties. A key technological feature is the precise control of each individual power semiconductor element, especially in transient conditions. This is important since the converter switches the high voltage on and off to create the desired AC waveforms.

The IGBTs are designed to limit the excessive overcurrents and transient voltages that can occur due to faults in the AC system, thereby ensuring that the system can be safely operated at such times. Under certain extreme conditions, eg a DC cable insulation failure, the antiparallel diodes integrated in the IGBT modules have to be able to withstand high surge currents to allow the plant to be safely shut down without damage to the installation.

Another special feature of the IGBT modules developed for HVDC Light is that they are designed for easy series connection.

All the series-connected IGBTs belonging to a valve have to be turned on or off simultaneously 13. Fiber-optic links carry these control signals to each individual IGBT. To ensure that all the power devices share the voltage equally during switching and blocking, the IGBT parameters that determine the switching speed and blocking impedance are carefully controlled during manufacture of the devices. Additional features, such as external voltage divider circuits and a gate unit designed for these tasks, make sure that the voltage across each individual IGBT is very precisely controlled.

Certain mechanical and thermal requirements also have to be met by the series-connected IGBTs. For instance, they have to be insulated from ground potential, which is not easy when dealing with converters operating at DC link voltages that may reach 100 kV or higher. In HVDC Light, the IGBT chips and the antiparallel diodes are mounted together in a presspack housing, similar to the packaging of traditional high-power thyristors. The IGBTs are stacked between coolers and there is a gate unit and a voltage divider for each, forming an IGBT assembly. Each gate unit is driven by a supply unit, which takes power from the voltage terminals of the IGBT. A large number of these series-connected assemblies are clamped together, under pressure, to form the IGBT 'stacks' which are used to build the converter. By testing the stacks before transporting them in the converter enclosure to the site, commissioning can be carried out much faster 14.

The road to high reliability

Although extensive measures are taken to ensure overall system and device protection, there will always be a small risk of device malfunction in complex systems with large numbers of individual components. Systems which, like HVDC Light, operate at high line voltages, normally have many devices connected in series. One large HVDC Light station handling, for example, 200–300 MW, has a total of more than 1000 IGBT assemblies. Adding extra devices to the stack of series-connected devices builds redundancy into the system, making it possible to operate the transmission link even if some of the power devices fail, while securing high system availability and limiting the need for periodic maintenance.

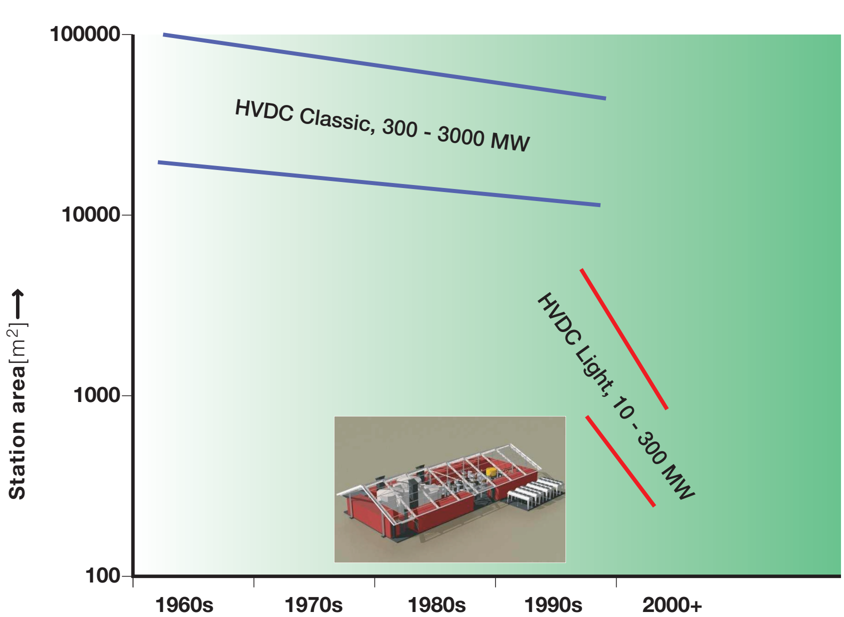
A precondition for redundancy of this kind is the ability of the devices to fail in a controlled way, creating a short circuit with sufficiently low resistance to be able to conduct the total system current. Following up on a comprehensive research and test program, ABB has developed a new family of high-power presspack modules to meet these criteria. They are designed to handle voltages in the 2500 to 4500 V range and phase currents from 500 A to 1500 A, making them ideal as building blocks for high-voltage, high-power installations. In the unique concept that was developed, a proprietary pressure device ensures that each chip has just enough force applied to it for the minimum electrical contact resistance. Besides increasing the reliability, this allows larger tolerances to be used for the mechanical structure used to build the IGBT stacks, thus improving the overall cost-efficiency of the system.

A growing field of applications

Power electronics-based solutions are increasingly being preferred to traditional electromagnetic installations for T&D applications. As a rule, these advanced solutions lead to an improvement in the efficiency and functionality of the existing electricity infrastructure; a case in point is the use of DC links in back-to-back configurations to provide interconnectivity between separate grids and improve network stability.

Another area in which power electronics is driving growth is microgrid technology, where it is essential for connecting small-scale distributed generation units and renewable energy sources to individual consumers and the utility network. The economic operation of turbines rated below 100 kW has been made possible by the availability of cost-efficient electronic converters which can transform the electrical energy from high-speed generators to 50/60-Hz AC power. Electricity from fuel cells, wind turbines and solar panels is generated at low DC voltage levels, and power electronics solutions incorporating high functionality and exceptional cost-efficiency are needed to convert it to usable voltages and frequencies. As renewable energy resources are usually located some distance from the large cities, new power

15 Station area requirements for HVDC installations



electronics-based technologies, such as HVDC Light, will allow the energy to be collected and fed, in an environmentally friendly way, into the power grid for transmission to end-users. The new breed of power semiconductors, with a functionality not unlike that of mass-produced integrated circuits and manufactured using similar technologies, is creating new ways to benefit from the economies of scale known so well from the semiconductor industry.

Another advantage of the new power electronics-based technologies is that they allow the size of electricity infrastructures to be considerably reduced, minimizing environmental, especially visual, impact and freeing valuable space and resources for other uses. The development of the different technologies for HVDC installations 15 underscores this trend. Compact installations will be important for an increasingly wider range of applications, eg for offshore facilities, feeding power into large cities, and for connecting large numbers of distributed generation units, located in sensitive locations, to the power grid.

The way forward

State-of-the-art power semiconductors have, over the past 40 years, created possibilities and defined solutions for the advanced control of power flow in many electrical systems. New device concepts and technology developments have led to innovations which have tended to make power electronics the technology of choice for growing numbers of industrial, traction and power transmission applications. The most recent advances, allowing high-frequency switching for cost-effective power conversion in the 100s of MW range, point to a more widespread use of power electronics in the T&D sector. This change of paradigm continues the ABB tradition of turning innovative system solutions into reality by pushing the technology limits of power semiconductors. Encouraging results from the R&D front – high-voltage IGBTs based on silicon and rectifiers based on silicon carbide are two cases in point – show that this is the way forward.

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