Power electronics applications in utilities

Semiconductors are a key enabler for power networks

CLAES RYTOFT, PETER LUNDBERG, HARMEET BAWA, MARK CURTIS – The power sector is changing rapidly due to ever increasing levels of electricity consumption, increased use of alternative, often remote, energy sources, and a greater focus on energy efficiency and grid reliability. Developments in power semiconductors and the use of this technology in various power-electronics-based applications are facilitating many of these changes. Power semiconductors are the key building blocks of power-electronics-based switching devices that control the flow of electricity and convert it to the wave form and frequency required for different applications. Semiconductors lie at the heart of many power technologies and are a key enabler shaping the grid of the future.

Traditionally, power networks were built around large centralized power plants, generating predictable and controllable power that was supplied to the power grid in a stable manner. One-way power flow was maintained in these grids despite hourly fluctuations in demand. Today, similar hourly fluctuations in demand exist, but increased reliance on renewable power sources installed to help reduce CO_2 emissions has meant that power grids also must cope with fluctuations in power supplies. These intermittent and variable energy sources (eg, solar and wind) highlight the need for energy storage, as well as systems to coordinate available sources of power generation with varied patterns of consumption.

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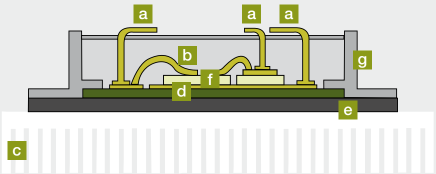
Fluctuations in the supply and demand for power can, to some extent, be attuned to one another through energy trading; however, transporting power efficiently from source to consumer, across adjacent networks, possibly over long distances and in both directions, presents a variety of challenges. These challenges are further exacerbated by the ever increasing demand for power, which must be satisfied while lowering greenhouse gas emissions. The provision of greater capacity to cope with electric vehicles and greater demand management will add further complexity, providing the impetus for the evolution of smarter, more flexible and reliable grids.

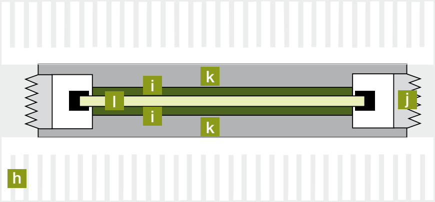
A variety of technologies pioneered by ABB have been developed and introduced to help the power industry fulfill these obligations. The technologies rely upon power semiconductors, which explains ABB's recent expansion of its production facilities. The manufacture and continued development of specialized power semiconductors ensures that ABB remains at the forefront of this technology. ABB will join the power industry in its task to develop flexible, efficient and reliable grids through the introduction of innovative power-electronics-based solu-

1 Semiconductor housing technology

In insulated housing the semiconductor ➔ f is galvanically isolated from the heat sink ➔ c. Electric contacts within the module are provided by bonding wires. In case of device failure, these wires tend to evaporate and the module ceases to conduct. In pressure-contact housing the load current enters through one surface ➔ k and leaves through the opposite surface. Low electrical and thermal resistances of the contacts are assured through high mechanical pressure on the surfaces. In the event of failure, the silicon semiconductor ➔ l and the molybdenum in ➔ i will melt and fuse so that the current can continue to flow.

➔ a Power and control connections
➔ b Bonding wire
➔ c Heat sink
➔ d Ceramic (usually AlN)
➔ e Base plate (usually AlSiC)
➔ f Semiconductor
➔ g Housing
➔ h Heat sink
➔ i CTE[1] compensation (Mo)
➔ j Housing (ceramic)
➔ k Copper
➔ l Semiconductor





Virtually all commercial power semiconductors are silicon-based; however, continuous optimization of silicon material technology has brought its performance very close to its physical limits. This means that the potential for further improvement in this aspect of the design is limited; however, semiconductor device housing still has considerable potential for improving performance.

There are essentially two forms of high-power semiconductor housing. The main difference between them is that in the insulated module, the electrical circuit is galvanically isolated from the heat sink by a ceramic insulator, whereas in the pressure-contact design, the current flows vertically through the entire module, ie, also through the heat sink.

Both of the housing forms are suitable for insulated-gate bipolar transistors (IGBTs) and integrated gate-commutated thyristors (IGCTs). However, in practice, IGCTs are currently available only in a pressure-contact housing, while IGBTs are available in both variants. The insulated housing currently dominates systems with low output powers (mostly below 1 megawatt), since the circuit can be constructed at lower cost. The pressure-contact housing, on the other hand, is preferred for output powers in excess of 10 MW. There are several reasons for this preference. The two most important are discussed here:

- In systems with very high power outputs, semiconductors must be connected in parallel and/or in series. For the latter, pressure-contact housings present a considerable advantage, as the modules can be arranged in a stack, separated only by heat sinks. One example of this is in HVDC power transmission installations, in which up to 200 modules are connected in series.
- A pressure-contact housing must be used if the application requires a guaranteed uninterruptible current flow (eg, a current-source inverter). In a pressure-contact housing, the metallic poles fuse if a semiconductor fails, thereby ensuring a low-impedance current path. Conversely, in an insulated housing, the current flows through bonding wires, which evaporate upon a high-current pulse, during a fault, leaving the circuit open.

Footnote

[1] CTE is the coefficient of thermal expansion

tions using high-power semiconductors designed and developed to provide better performance characteristics ➔ 1.

Renewable energy

Generally, the most reliable renewable energy sources, such as high winds, intense solar radiation or large volumes of moving water, are found in remote regions of the world, far from population and industrial centers. Long-distance power transmission, using a conventional alternating current (AC) transmission system, is less efficient in some such cases and cannot be deployed, for example, where undersea cables are required to connect offshore wind turbines to the mainland. The problem is that AC oscillates at 50 or 60 cycles per second (ie, 50 / 60 Hz) regardless of whether it is at extra-high voltage, high voltage, medium voltage or low voltage. For each cycle, an AC cable is charged and discharged to the system voltage. This charging current increases with cable length. At a certain length, the charging current of the cable and its sheath become so large that no useful power remains, but long before reaching this length, power transmission becomes uneconomical. A direct current (DC) cable, on the other hand, has no corresponding charging current. In the DC cable, all current is usable. To transport energy efficiently to consumers over large distances with low losses, ASEA, ABB's Swedish forerunner, developed a DC transmission system with a power rating of 30 megawatts (MW) in the early 1950s. The system was first used to link the island of Gotland to the Swedish mainland ➔ 2. This link was significant because it was capable of bulk electricity transmission with low losses through undersea cables, giving the islanders reliable supplies of cheap electricity. Since that first installation, ABB has continued to develop the technology, replacing earlier fragile mercury-arc valves, used to convert AC to DC and DC to AC, with robust power-semiconductor-based applications. Today some of the largest cities, including Shanghai, Delhi, Los Angeles, and Sao Paulo, rely on the delivery of huge amounts of electricity, often over thousands of kilometers, through HVDC transmission systems. Similarly ABB has installed several submarine HVDC cable interconnections between various western European countries, such as the NorNed project, which connects Norway with the Netherlands. Furthermore, ABB has connected offshore wind farms to the mainland, including the BorWin1 project, the most remote offshore wind farm in the world located 128 kilometers from the German mainland in the North Sea. To achieve these feats, ABB has developed a range of HVDC transmission systems to suit a variety of specialized applications.

> ABB will join the power industry in its task to develop smarter, more flexible, efficient and reliable grids.

2 Cable laying for the Gotland HVDC link in 1954

3 Thyristor valve hall

4 2,071 km UHVDC connection from Xiangjiaba to Shanghai

HVDC Classic

HVDC Classic, as the name suggests, was the pioneering technology and initially made use of mercury valves. Today the power conversions are made using thyristors (see devices described in “Semiconductors demystified" on page 26 of *ABB Review* 3/2010). The thyristors are series connected and arranged in thyristor modules, where each thyristor can withstand 8.5 kilovolts (kV). These modules (in pressure-contact housing) are then series connected in layers to create thyristor valves of full voltage ➔ 3. The switching frequency of each thyristor is 50 Hz (or potentially 60 Hz) in this application. This system is used primarily to transport bulk electricity over long distances, either overland or underwater, allowing electricity grids to be interconnected for greater stability where conventional AC methods cannot be used. Today’s HVDC transmission systems have very high power handling capability and excellent reliability records. Converter losses are low and equipment costs are minimized in this comparatively mature technology. HVDC will play a major role in the emerging grids of the future. ABB is uniquely positioned with the capability of manufacturing all the key components from cables, converters, and transformers to power semiconductors.

Ultra-HVDC

More recently, advances in technology have allowed voltage ratings of up to 800 kV using UHVDC (ultra-HVDC). In order to reach this power level a new 6” (inch) thyristor of 130 cm^2 was introduced that increased the normal current to 4,000 A, without affecting the switching frequency. Such innovations represent the biggest leap in transmission capacity and efficiency in more than two decades. The technology is being used to transmit 6,400 MW of power over a distance of 2,071 km from the Xiangjiaba hydroelectric power plant in southwest China to Shanghai in the east, providing clean electricity for around 31 million people ➔ 4.

HVDC Light

A useful adaptation of HVDC Classic has been the 1990s development of ABB’s HVDC Light®. This system uses transistors rather than thyristors for the power conversion process. HVDC Light also enables long-distance transmission using low-impact underground and underwater cables or overhead lines. However, the use of high-speed gate-controlled semiconductor switches, ie, insulated-gate bipolar transistors (IGBTs), have made it possible to generate state-of-the-art voltage source converters (VSC) as an integral part of the system, able to rapidly inject or absorb reactive power. Their superior ability to stabilize AC voltage at the terminals has made this technology ideal for wind parks, where the variation in wind speeds can cause severe voltage fluctuations. Similarly, their outstanding controllability and flexibility has seen their increasing use to connect oil and gas rigs to the mainland and to provide grid interconnections.

5 StakPak™ module containing IGBTs

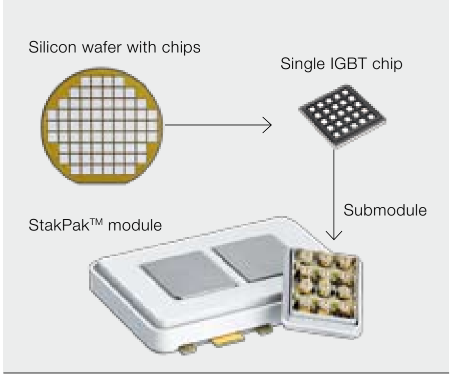


ABB has installed several submarine HVDC cable interconnections between various western European countries, including the NorNed project, a 580 km link between Norway and the Netherlands.

6 IGBT valve hall

7 Major HVDC Light and SVC installations

Project	Number of converters	Year in operation
1 Hällsjön	2	1997
2 Hagfors (SVC)	1	1999
3 Gotland	2	1999
4 Directlink	6	2000
5 Tjæreborg	2	2002
6 Eagle Pass	2	2000
7 Moselstahlwerke (SVC)	1	2000
8 Cross Sound Cable	2	2002
9 Murraylink	2	2002
10 Polarit (SVC)	1	2002
11 Evron (SVC)	1	2003
12 Troll A	4	2005
13 Holly (SVC)	1	2004
14 Estlink	2	2006
15 Ameristeel (SVC)	1	2006
16 ZPSS (SVC)	1	2006
17 Mesnay (SVC)	1	2008
18 Martham (SVC)	1	2009
19 Liepajas (SVC)	1	2009
20 Siam Yamato (SVC)	1	2009
21 BorWin 1 (Nord E.ON 1)	2	2010
22 Caprivi Link	2	2010
23 Valhall	2	2010
24 Liepajas Metalurgs (SVC)	1	2010
25 Danieli – GHC2 (SVC)	1	2011
26 Danieli – UNI Steel (SVC)	1	2011
27 EWIP	2	2012

The characteristic, above all others, that makes HVDC Light so controllable is mainly due to the IGBT semiconductor devices used in its assembly. Like thyristors, IGBTs can be connected in series to increase the voltage ratings.

However, unlike thyristors, which are controlled by a gate current, only a small voltage signal is required to control their switching. To build an HVDC Light system with power rating of 300 MW, 6,000 StakPak modules, containing around 200,000 IGBT chips, are connected in series ➔ 5 and ➔ 6. Each StakPak module is made of several sub-modules (can be two, four or six). The switching frequency of the IGBT can be determined according to the application and is normally in the range of a couple of hundred hertz up to 1 kHz. The assembly of IGBTs in this way creates a compact, highly controllable power electronic converter able to provide voltage stability even in regions of the network with no additional power sources. The first HVDC Light project was the 10 kV trial transmission in Hällsjön-Grängesberg, which was completed in 1997. Since then many converter stations have been built, the largest of which has a maximum turn-off current of 4,000 A in normal operation and can withstand about 18 kA during short-circuit conditions ➔ 7.

ABB is uniquely positioned to help build the grids of the future with the capability of manufacturing all the key components from cables, converters, and transformers to power semiconductors.

Flexible AC transmission systems (FACTS)

The AC power system has always faced challenges with reactive power. This component of AC power is consumed by capacitors, transformers and inductive motors, which are common elements in an AC grid. The power loss due to these elements on the system results from the production of magnetic fields (in the case of inductive elements), or electric fields (in the case of capacitive elements), which effectively reduce the real power available in the system (for an explanation of active and reactive power see page 35 of *ABB Review* 3/2009). Reactive power compensation devices, such as capacitor banks ➔ 8, can be switched in to the system automatically under inductive conditions, providing a higher system voltage, or reactors can be used to consume vars (Volt-ampere reactive power) from the system, lowering the system's voltage under capacitive conditions. If reactive power is not compensated locally it will be pulled across transmission lines, destabilizing the network, which can cause blackouts. The term FACTS encompasses a group of technologies that enhance the security, capacity and flexibility of power transmission systems. These technologies can be installed in new or existing power transmission lines, either in series, eg, using thyristor controlled series capacitors (TCSCs) or thyristor-controlled series reactors (TCSRs); or in parallel, eg, with static var compensators (SVCs) or static synchronous compensators (STATCOMs). These devices optimize power flow and stabilize voltages by compensating for reactive power using power electronics.

TCSCs and TCSRs

Thyristors can be used to automatically switch in capacitors, using TCSC, or reactors, using TCSR, to stabilize the voltage. TCSCs are especially useful in stabilizing voltages at interconnections in transmission grids and have been used to interconnect Brazil's northern and southern power systems. Since the spring of 1999, Eletronorte of Brazil has been operating a TCSC and five fixed series capacitors (SC) supplied by ABB in Eletronorte's 500 kV interconnector between its northern and southern pow-

8 Capacitor bank

9 TCSC at Imperatriz, Brazil

er systems ➔ 9. ABB has installed about 1,100 Mvar of series capacitors providing dynamic stability for both interconnected electric utility systems.

SVC

With both HVDC Classic and UHVDC, SVCs must be deployed at the point at which these systems join the AC network to inject or absorb reactive power. This is because HVDC systems can only transmit active power, which means such systems form an effective barrier to reactive power flows. While this can prevent the cascading domino effect of reactive power flows that can spread across the entire network, causing voltage collapse and blackouts, it can also reduce available sources of reactive power. To compensate for this shortfall in reactive power, SVCs must be installed at the HVDC connection point to ensure stability, providing a local facility to absorb or inject reactive power.

One of the consequences of interconnecting electricity networks for power trading has been an increased vulnerability of the grid to spreading problems. The advantage of using HVDC systems to connect AC grids has been twofold; they form a barrier to reactive power flows, as described above, and they allow electricity mains of different frequency or networks of the same nominal frequency, but with no fixed phase relationship, or both (ie, different frequency and different phase number) to be connected. Of course, such connections do not have to be long; all that is required is a short back-to-back HVDC station with both static inverters and rectifiers in the same building.

STATCOM

In addition to HVDC Light, which in itself uses IGBTs to provide VSC capabilities to rapidly inject or absorb reactive power, SVC Light® uses IGBTs in a similar way. SVC Light is a static synchronous compensator (STATCOM) that is similar in function to thyristor-based SVCs, but based on a VSC. The IGBT semiconductors for SVC Light are packaged in StakPaks and connected in series to cope with the required voltage ➔ 10. The greater control afforded by IGBTs provides power quality improvements capable of mitigating voltage flicker caused by customers running electric arc furnaces. These furnaces are heavy consumers not only of active power, but also of reactive power. To compensate for the rapidly fluctuating consumption of reactive power of the furnaces, an equally rapid compensating device is required. This rapid response is brought about by state-of-the-art IGBT technology. The advent of such continuously controllable semiconductor devices capable of high power handling, enables SVC Light to handle highly dynamic reactive power requirements in the grid ranging from tens of megavolts ampere (MVA) up to ratings exceeding 100 MVA.

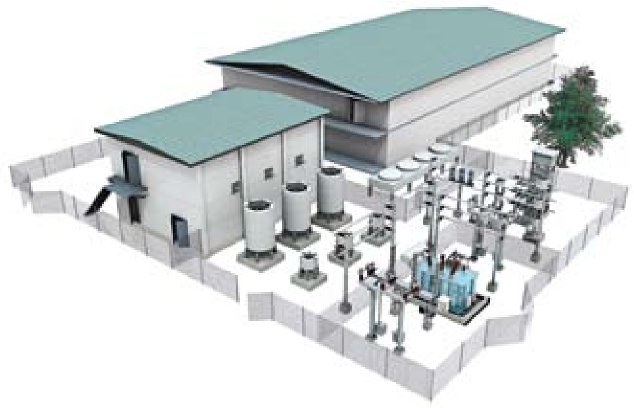
SVC Light with energy storage

With greater reliance on renewable energy comes a degree of grid instability. To further enhance stability and reliability, ABB has introduced its latest addition to the FACTS family, SVC Light® with Energy Storage ➔ 11. This is a dynamic energy storage system based on Li-ion batteries that can not only deliver reactive power, like ordinary SVC Light, but can also deliver active power, hence providing an alternative to transmission and

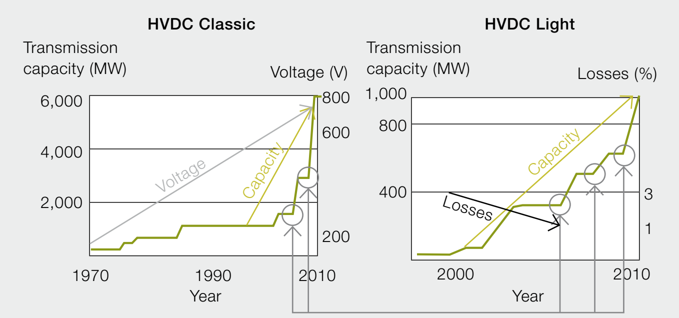
10 SVC Light stack

The provision of greater capacity to cope with electric vehicles and greater demand management will add further complexity to the power system, providing the impetus for the evolution of smarter, more flexible and reliable grids.

11 SVC Light with Energy Storage



12 Growing transmission capacity in recent years



Capacity up 6 times since 2000
Voltage up 100 kV
to 800 kV since 1970

Capacity up 10 times since 2000
Losses down from 3% to
1% per converter since 2000

SVC Light with Energy Storage enables the independent and dynamic control of active as well as reactive power in the grid.

distribution reinforcements for peak-load support. The present rated power and capacity of storage is typically in the 20 MW range for periods of approximately 15 to 45 minutes, but this technology can be scaled up to 50 MW of power for 60 minutes and more.

MACH2™ control system

The introduction of power electronics technology to the electric grid presents an opportunity to effectively manage the magnitude and direction of power flow. To maximize and safeguard performance, efficient tools to control, monitor, and analyze HVDC transmission systems have been developed. ABB's MACH2™ system is a high performance HVDC control and protection system. It is used today in conventional HVDC, SVC and SVC Light and a number of other applications to control the switching of semiconductors at very high speed and accuracy to precisely control voltage and power.

In today's power grids a greater degree of sophistication is required to ensure that stable, reliable power is delivered on demand despite the intermittent nature of the renewable energy sources, such as wind, solar, wave and tidal power. To facilitate the new demands placed on the power grid, innovative power electronic devices with better performance characteristics are continually being added to new and existing grid structures.

The performance characteristics of HVDC Classic and HVDC Light have grown rapidly over the last 10 years → 12. Advances in the application of semiconductor technology will continue into the future as visionary projects such as Desertec and DC grids become a reality.

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