A single-source supplier

ABB enjoys a unique position in HVDC systems technology, being the sole company able to supply all key components. An HVDC substation includes converter valves with power semiconductors, cooling equipment, transformers, bushings and other DC and AC power products, and in many cases, cable connections.

Heart of the converter

High-voltage power semiconductor devices

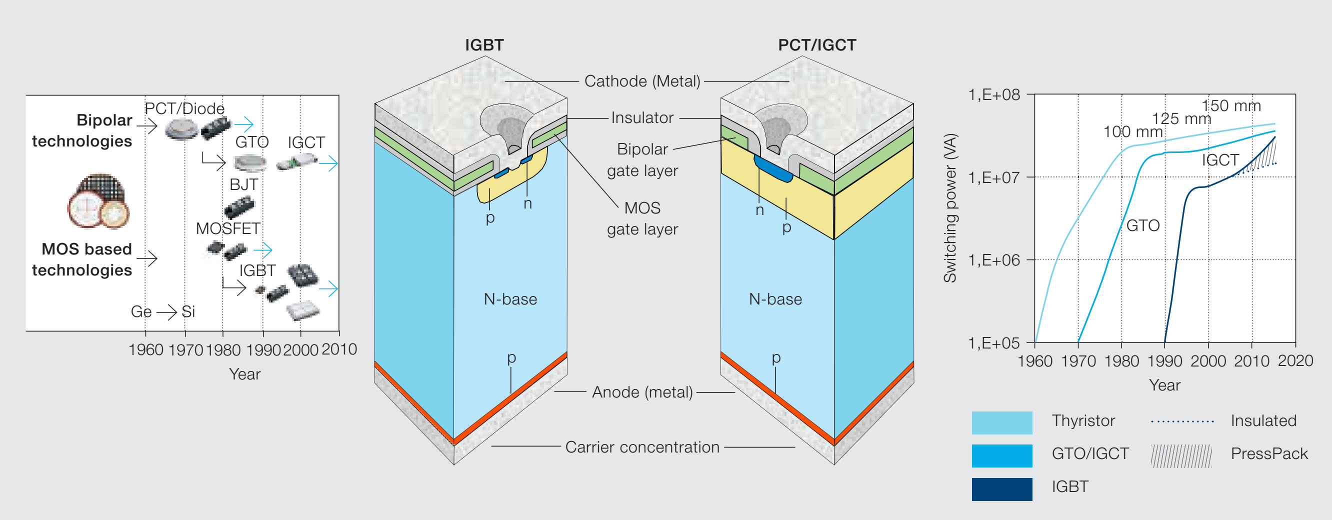
MUNAF RAHIMO, SVEN KLAKA – Silicon-based high-voltage semiconductor devices play a major role in megawatt power electronics conversion. In particular, advances in ultrahigh-voltage semiconductors have over the past few decades led to tremendous improvements in high-voltage direct current (HVDC) transmission. The power device is considered a main enabler for the growing demands of modern grid systems in terms of increased power levels, improved efficiency, greater control and integration of renewable energy sources.

The power electronics revolution, which over the past few decades has swept across the power delivery and automation sectors, has opened up a wide range of possibilities in terms of controlling the way electrical energy is transported and used. At the heart of this revolution lies the power semiconductor device: This device performs the actual task of modulating the energy flow to suit the demands of the application. The main trend in the development of power devices has always been increasing the power ratings while improving overall device performance in terms of reduced losses, increased robustness and better controllability, and improving reliability under normal and fault conditions.

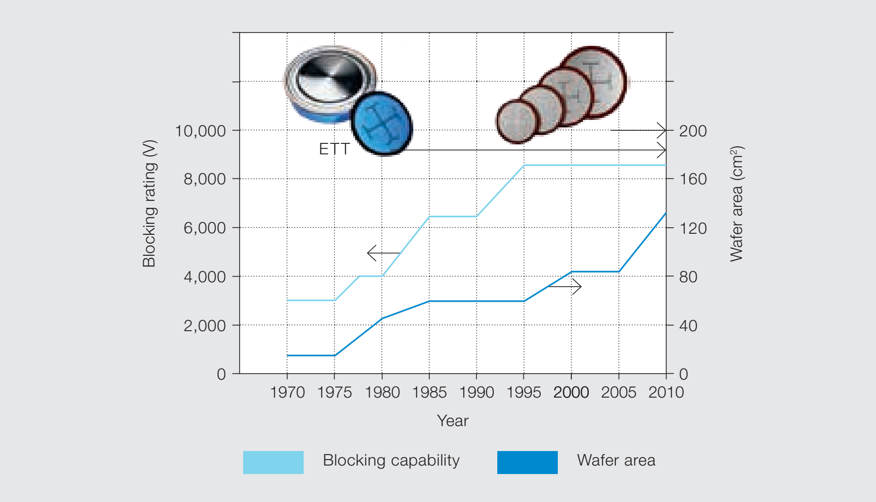
The HVDC-applications market is small but important for semiconductors. Progress in the domain of power devices has in the past largely been dependent on technologies developed for lower power applications, which were then scaled to handle higher voltages and currents. In HVDC applications today, the two main types of switching devices are the phase-controlled thyristor (PCT) and the insulated-gate bipolar transistor (IGBT). Also important is the power diode found in a range of applications spanning rectification, snubber and freewheeling.

Different power-semiconductor-based circuit topologies such as current source converters (CSCs) and voltage source converters (VSCs) are employed for the AC/DC conversion process. For long-distance and multi-gigawatt power transmission, PCT-based CSC topologies are widely

1 Power device evolution and basic structures



2 PCT evolution and 150mm PCT rated at 8.5 kV / 4,000 A for UHVDC



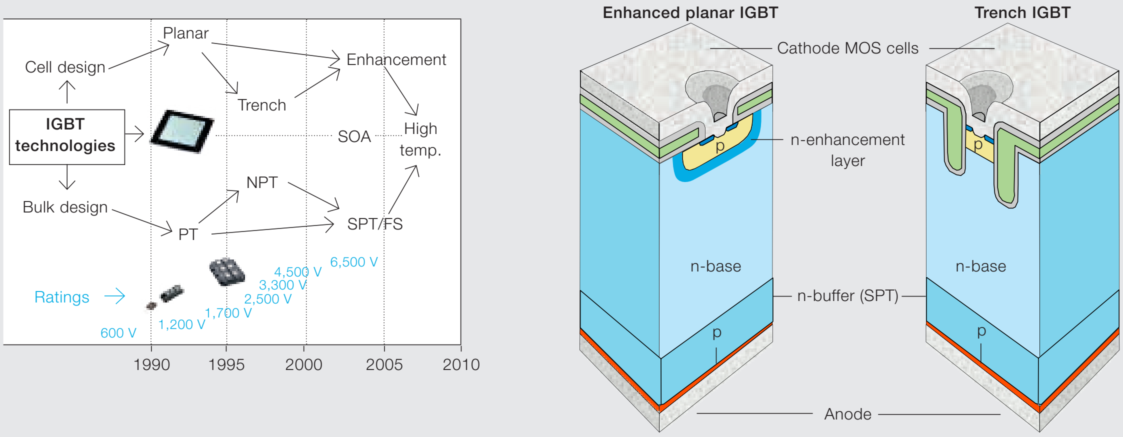
used due to the overall low system losses. For relatively shorter distances and lower power levels, IGBT-based VSC conversion is becoming the system of choice due to a number of advantageous integration and control features (especially when taking into account the introduction of renewable energy into the grid). Despite the existence of optimized high-voltage devices with attractive electrical characteristics, the main development trend continues to seek higher power and superior overall performance.

Power semiconductor devices for HVDC applications

High-voltage power semiconductors differ from their low-voltage counterpart in a number of structural aspects. First, they include a wide and low n-doped base region at the pn-junction to support the high electric fields required for the high voltage ratings. For current-carrying capability with low losses, they require large active areas and highly doped contact regions to provide high minority carrier (holes) injection levels for modulating the low doped n-base, and good ohmic contacts to the outside world. Current normally flows in the vertical direction (perpendicularly to the wafer surface) in devices whose voltage range exceeds 1 kV. Today, silicon-based devices can be designed with good overall performance parameters up to 8.5 kV for a single component. It is important to note here that power semiconductors employed in grid systems do not differ from those

The power electronics revolution has opened up a wide range of possibilities in terms of controlling the way electrical energy is transported and used.

3 Evolution of IGBT technology and modern structures



> For relatively shorter distances and lower power levels, IGBT-based VSC conversion is becoming the system of choice.

employed in other power electronics applications such as traction and industrial drives.

Nevertheless, for HVDC applications operating in the hundreds of kilovolts range, devices are normally connected in series to support the total DC-line voltage. The choice of the single device voltage rating employed in these systems depends largely on the performance/cost calculation for a given topology and operational parameters. Devices rated for lower voltages normally have favorably lower overall loss figures but imply that a larger number of components are needed.

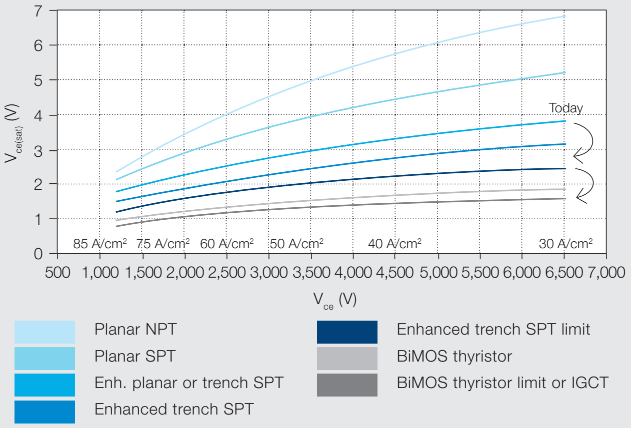
The basic structure of a PCT and IGBT is shown in ➔ 1 as is its evolution over the years along with other device concepts such as the integrated gate-commutated thyristor (IGCT). The historical increase in the switching power levels of high-voltage devices is also shown. The PCT is a thyristor bipolar device, which is mainly characterized by its favorable excess carrier distribution for low on-state losses in conduction mode. The IGBT, on the other hand, is a MOS (metal-oxide semiconductor)-controlled device with a bipolar effect for achieving low on-state losses.

The PCT

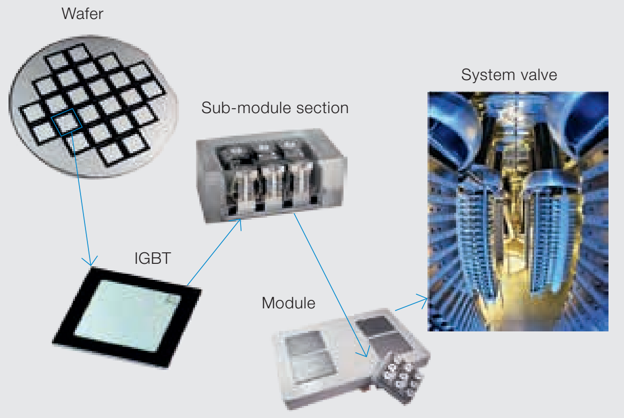
In contrast to the IGBT, the PCT is not a turn-off device. It is nevertheless the device of choice for line-commutated CSC HVDC systems due to its exceptionally low on-state losses and very-high-power handling capability. Until very recently, state-of-the-art single devices were rated at 8.5 kV with a total diameter of 125 mm. With the increase in demand for even higher power HVDC system ratings, larger area 150 mm, 8.5 kV PCTs with current ratings up to 4,000 A were developed for the latest Ultra HVDC systems operating at ± 800 kV with total transmission power exceeding 7 GW. The PCT evolution, including the new 150 mm PCTs and the UHVDC system valves consisting of series connected PCTs, is shown in ➔ 2.

> The PCT is the device of choice for line-commutated CSC HVDC systems due to its exceptionally low on-state losses and very-high-power handling capability.

4 High-voltage IGBT technologies on-state losses $V_{ce(sat)}$



5 IGBT application from single chip to system valve



Further technology developments are underway to increase current ratings to exceed 6,000 A while lowering conduction losses.

The IGBT

The IGBT is a MOS-controlled bipolar switch and presents the inherent advantages of that technology including a controlled low-power driving requirement and short-circuit self-limiting capability. The IGBT has experienced many performance breakthroughs in the past two decades ➔ 3.

The fast progress in IGBT cell designs (planar, trench, enhancement layers) and bulk technologies such as punch-through (PT), non-punch-through (NPT) and soft-punch-through (SPT) has led to their widespread deployment in many high-voltage applications. Today, high-power IGBT press-pack and insulated modules have ratings ranging from 1,700 V / 3,600 A to 6,500 V / 750 A. The most recent trends have targeted lower losses by using thinner n-base regions (SPT) and plasma enhancement layers and/or trench cell designs as shown in ➔ 3 accompanied by higher SOA and higher operating temperature (HT) levels. Similar development efforts targeted an improved diode design to match the latest IGBT performance. The free-wheeling diodes play a very important role in the application during normal switching and under surge current conditions. The current IGBT platform employed in grid applications is based on an enhanced-planar cell design (EP-IGBT), which has enabled the establishment of a new technology curve benchmark over the whole IGBT voltage range from 1,200 V up to 6,500 V as shown in ➔ 4. Future higher power densities and loss reductions are possible by implementing Enhanced Trench ET-IGBT cell designs, Emitter Switched Thyristor EST structures as shown in ➔ 4 and integration solutions such as the bi-mode insulated-gate transistor (BIGT).

A customized press-pack module (StakPak) was developed for series connection of IGBT and diode chips to be used in grid applications. The mechanical design is optimized to clamp the press packs in long stacks. The module remains fully functional due to its design with individual press-pins for each chip as shown in ➔ 5. Furthermore, the choice of materials is optimized to achieve high reliability.

Today, high-power IGBT press-pack and insulated modules have ratings ranging from 1,700 V / 3,600 A to 6,500 V / 750 A.

Munaf Rahimo
Sven Klaka
ABB Semiconductors
Lenzburg, Switzerland
munaf.rahimo@ch.abb.com
sven.klaka@ch.abb.com

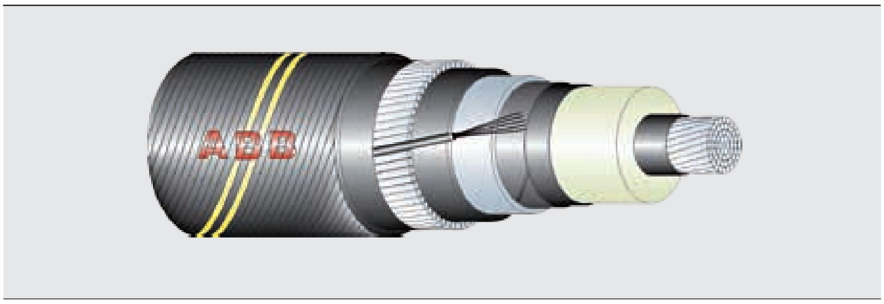
Crossing land and sea

High-voltage DC cables

THOMAS WORZYK, TORBJÖRN SÖRQVIST, OLA HANSSON, MARC JEROENSE – It is notable that Gotland 1, the very first modern HVDC project of the 1950s, featured an underwater link. Following this 1954 breakthrough, further HVDC cables were installed across the world. ABB has as of today delivered 2,300 km of mass impregnated DC cables.

1 Laying the Gotland cable in 1954

2 An extruded HVDC cable for submarine application, equipped with optical fibers for temperature monitoring



The Gotland 1 link ➔ 1 did not only feature the first submarine MI (mass-impregnated) HVDC cable, but it also heralded an era of onshore connections. A new link was built at Gotland in 1999 using an 80 kV extruded HVDC cable system. Three years later ABB installed the Murray Link at the antipodes using almost twice the voltage (150 kV) and more than double the length (180 km). The Murray Link is still today the longest land-based high-voltage cable in the world. The contracting of a number of extruded HVDC cable projects for offshore wind farms at ± 320 kV is a clear indication for the confidence in this technology. As of 2015, the energy supply of Lithuania will be supported by the record-breaking NordBalt project. With its 400 km submarine section, NordBalt will be the longest extruded high-voltage cable in the world. Once the DolWin2 cable system is complete, ABB will have installed more than 5,000 km of extruded HVDC cable ➔ 2–3.

> The Murray Link is still today the longest land-based high-voltage cable in the world.

Almost all modern HVDC cables are single-core. The simplicity of the design is one of the reasons for the significant reduction in required investment compared with HVAC. HVDC cables can be manufactured in many varieties. Round copper or aluminum conductors of large sizes can be used. There are two different insulation types used for HVDC cables: Mass-impregnated cables (MI) have a layered insulation made of special paper and impregnated with a

3 Cable history

HVDC and HVDC cables have always had a flavor of fascination – from the War of Currents between AC and DC at the end of the 19th century to the German “Energiewende,” engineers and even the public continue to discuss the fantastic possibilities of HVDC cables to transport large amounts of power over virtually unlimited distances. During the first half of the 20th century, HVDC research in countries such as Sweden, the United States and Germany focused on converter stations. The development of high-voltage cables principally served the widespread AC technology. Although some of the peculiarities surrounding HVDC cables were understood early on, manufacturing experience remained scarce. An HVDC cable system was built during WW II in Germany but was never commissioned due to the turmoil of war. It was later re-erected in Russia as an experimental line. A submarine HVDC connection between Norway and the Netherlands was proposed as early as 1933, 75 years before ABB realized this link.

ABB’s predecessor cable factory (Liljeholmens AB) performed HVDC tests on mass-impregnated cable in the 1940s, maybe sensing the upcoming interest in the market where grids were expected to grow after the war. At the same time, the work of Dr. Lamm in Ludvika resulted in mercury-arc valves with acceptable reliability.

As so often happens in technical development, not only ingenuity but its combination with pioneering spirit and a certain market situation lead to the breakthrough – and to the Gotland project. The Swedish State Power Board decided in 1951 to connect the Swedish Island of Gotland electrically to the mainland – a distance of 100 km. No other technology but a submarine HVDC cable could solve the task. It was a bold decision – nobody had done this before.

Bjurström, the mastermind of Liljeholmens AB at that time, presented the Gotland cable at the 1954 Cigré conference, in a paper humbly titled “A 100 kV DC cable.” The Gotland cable was a masterpiece of its time, engineered to be reliable. While it is quite easy to produce a few hundred meters of cable, the production and installation of extreme lengths is a very different business. Bjurström and his colleagues put all the best into the Gotland cable:

- Solid 90 mm^2 solid copper conductor in order to reduce disadvantageous conductor expansion under cable torsion in manufacturing or submarine laying
- 7 mm mass-impregnated insulation, comfortably exceeding physical requirements
- Extra-dense insulation paper in order to avoid partial discharges or ionization as it was called at that time
- Double lead sheath. Liljeholmens AB later developed a continuous lead sheathing machine, which improved the quality and emerged as a virtual standard in high-voltage cable sheathing
- Double armoring in the landfall cables

The cable design was so successful that the original Gotland cable link could be upgraded from 100 to 150 kV when power demand increased. A piece of the original cable was analyzed after decommissioning a few decades later and showed no signs of aging.

Today, only the double-lead sheath would be manufactured differently.

high-viscosity compound. The other type, the extruded insulation, comprises a polymeric insulation made by continuous extrusion of ultra-clean polymeric material. MI cables are a good choice for the highest ratings but extruded cables are catching up. Both insulation types are solid, ie, no harmful oil is spilled should the cable be damaged.

> The simplicity of the HVDC cable design is one of the reasons for the significant reduction in required investment when compared with HVAC.

Since the insulation must be protected from water, submarine HVDC cables always feature a metallic sheath serving as a water block and path for short-circuit currents. Extruded underground HVDC cables can instead use a lightweight metallic laminate sheath and a copper wire screen.

The HVDC cable can be dressed with tough outer plastic sheaths, or wire armoring for, eg, subsea applications. The extruded HVDC cable can be installed in the most challenging environments, such as the deep sea and vertical shafts ➔ 4.

Characteristics of HVDC cables

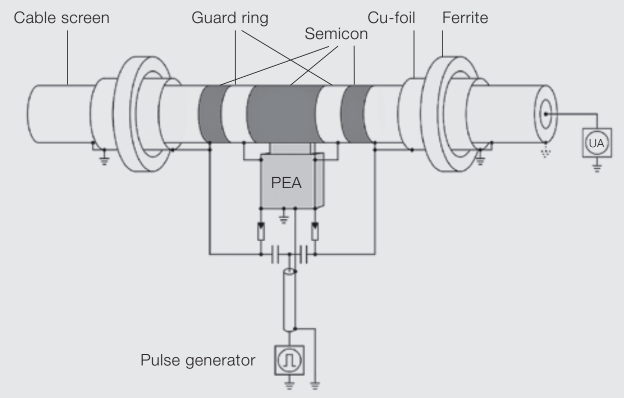
At first sight there is not much difference between an HVAC and an HVDC cable. Both contain a conductor, insulation, a water barrier and in the case of the submarine cable, armor. The main difference lies in the electrical high-voltage insulation.

From an electrical point of view, HVDC insulation behaves differently than its HVAC counterpart. While the electrical field – an important design and operational parameter – is defined by the permittivity in an HVAC cable, it is (also) controlled by the resistivity in the HVDC case. The resistivity of the insulation material depends in part on the temperature. A loaded cable generates heat in the conductor, which will typically result in a temperature drop across the insulation. The temperature distribution will have a corresponding effect on the resistivity distribution. As a result, the electrical field distribution may be inverted in a loaded HVDC cable compared with HVAC (where the electric field is always the highest at the conductor screen and decreases toward the insulation screen). The effect of field inversion is a well-known peculiarity of both mass-impregnated and extruded cable.

4 Selection of ABB’s groundbreaking HVDC cable projects

Project name	Location	DC voltage	Insulation	Year	Remarks
Gotland 1	Sweden	100 - 150 kV	MI	1954	First submarine HVDC cable ever
Baltic Cable	Sweden-Germany	450 kV	MI	1994	Highest Voltage, longest length at that time
Murray Link	Australia	± 150 kV	XLPE	2002	Longest underground cable system of all times.
NorNed	Norway-Netherlands	± 450 kV	MI	2008	580 km. Longest power cable system, all categories
SouthWest Link	Sweden	± 320 kV	XLPE	2015	First extruded HVDC system with combined cables and OH line.
NordBalt	Sweden-Lithuania	± 300 kV	XLPE	2015	Longest HVDC Light system, 400 km submarine cable route with cost-saving Al conductor

5 The PEA technique presents a reliable method to quantify space charge



The main difference between HVAC and HVDC cable lies in the electrical high-voltage insulation.

The development of the extruded cable took time: The physics of the polymer insulation under DC electric stress was a new area, and proper non-destructive measurement technology was not available. In the 1960s, theorists had predicted that so-called space charges would impact the electric field and therefore possibly have a negative effect on the performance of the cable. Space charges, as the term suggests, are charges that are present inside the insulation. These charges will affect the local field strength and “distort” the distribution of the electrical field. In the 1980s Tatsuo Takada in Japan presented a reliable measurement technology to quantify space charge in both magnitude and space. The measurement principle is called the pulsed electro-acoustic (PEA) method. ABB was one of the first companies to use it ➔ 5.

Applying this tool as well as a wide technology base in physics, chemistry and high-voltage engineering, ABB was able to develop 80 kV extruded cable systems. The technology has since been boosted to 320 kV.

Cable accessories for HVDC Light extruded cables utilize a combination of geometric and refractive field grading for capacitive field distributions and nonlinear resistive field grading for DC field distributions. The accessories are designed to ensure an appropriate electric-field level when subjected to time-varying voltages (such as lightning and switching impulses). DC field control is achieved by a continuous layer of nonlinear field grading material (FGM) connecting full potential to ground.

Thomas Worzyk
Ola Hansson
Marc Jeroense
ABB Power Systems
Lyckeby, Sweden
thomas.worzyk@se.abb.com
ola.hansson@se.abb.com
marc.jeroense@se.abb.com

Torbjörn Sörqvist
ABB Power Products
Alingsås, Sweden
torbjorn.sorqvist@se.abb.com

Conversion

HVDC valves

JONATAN DANIELSSON, BAOLIANG SHENG – The heart of the converter is the valve, which comes in two basic designs for HVDC Classic and HVDC Light®, based on thyristors and IGBT semiconductors, respectively.

Two different designs of thyristor-based line-commutated valves have been developed by ABB: a conventional base-mounted design with support insulators standing on the floor, and another (more frequently used) design with the valve suspended from the ceiling of the valve hall → 1. The latter design is particularly suitable for withstanding seismic stresses, but also offers cost advantages.

1 Valve suspended from the ceiling of the valve hall

The design uses a modular concept to ensure high reliability while retaining the flexibility to design valves according to customer requirements and preferences. A valve is built up with one or several layers depending on the required voltage withstand capability → 2. Each layer consists of series-connected thyristor modules with intermediate current-limiting reactors, corona shields and piping for the cooling liquid. The individual parts are supported by a mechanical structure with a central shaft running vertically through the structure with ladders and working platforms for easy access.

Thyristor modules

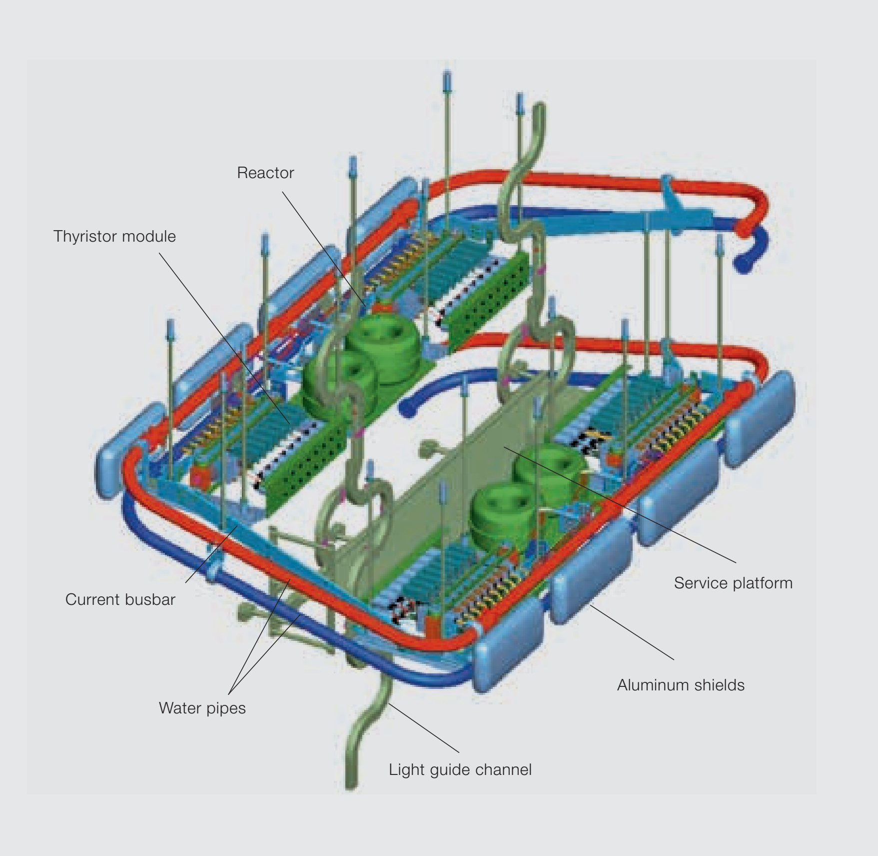
Thyristor modules are of a mechanically standardized compact design. For the sake of reliability they have a minimum of electrical components and connections. The main components are thyristors and their voltage dividers, control units and heat sinks.

> The design uses a modular concept to ensure high reliability while retaining the flexibility to design valves according to customer requirements and preferences.

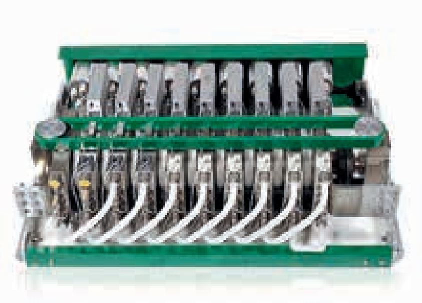
The modules are of compact design for easy access during maintenance. The design allows components to be exchanged without opening the water cooling circuit → 3.

Each module contains a number of thyristors connected in series. Continuous thyristor development enables them to handle ever-increasing voltages and currents, while also reducing conducting and switching losses. The first HVDC valves designed by ABB were for the upgrading of the Gotland transmission – they used thyristors with an area of 5 cm². The next valve design (used for the Skagerrak transmission) featured double-sided cooling of the thyristors, which had an area of 8 cm². Today thyristors have an area of up to 130 cm² capable of withstanding continuous currents up to 4,500 A and short-circuit current up to 50 kA, eg, for the Xiangjiaba-Shanghai ± 800 kV Ultra-HVDC project [1].

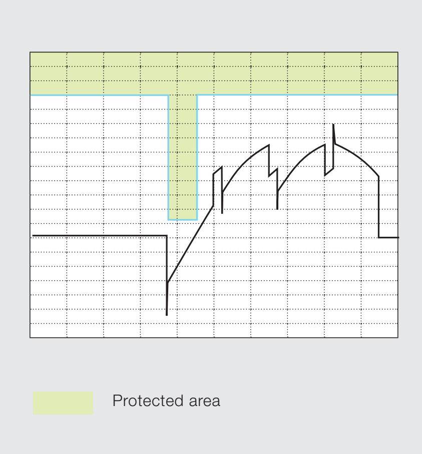
2 Single layer of a valve



3 Thyristor module



4 Voltage across thyristor level



A switching position is built up from a thyristor with two parallel circuits, each consisting of a damping circuit and a DC grading circuit, as well a TCU (thyristor control unit). The TCU converts the optical firing pulses from the control system to electrical signals to trigger the gate that fires the thyristor. The TCU includes state-of-the-art built-in functions that protect it against overvoltages during the reverse recovery period (after a thyristor turns off) as well as from high voltages in the forward blocking state ➔ 4.

By using this hybrid technique, ABB is able to provide a very compact TCU. ABB's service record is also unbreakable: Of the more than 19,000 thyristors installed since 2000, only four thyristor failures have been reported. This demonstrates the superior design of electrically triggered thyristors.

IGBT-based voltage source converter valves

The use of IGBT-based voltage source converters (VSCs) in HVDC power transmission was a breakthrough. Its first application was in a 3 MW HVDC Light test installation in Hällsjön in 1997. Since then, 20 VSC HVDC power transmissions have been installed or are under construction by ABB alone [2].

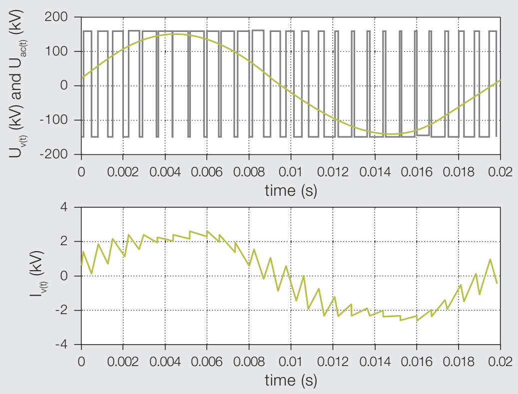
> The liquid in the closed valve cooling system is continuously passed through a deionizing system to keep its conductivity low.

Two types of VSCs have been developed for HVDC transmission: the "switch" type and the cascade two-level (CTL) or "controllable voltage source" type. The choice of converter type mainly depends on the application.

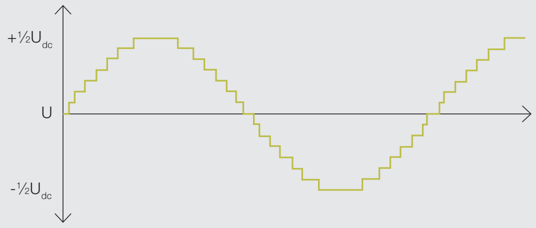
A switch-type valve has a close apparent resemblance to conventional thyristor valves: A large number of series-connected IGBT devices are switched simultaneously. Pulse-width modulation (PWM) is used to achieve a good approximation of a sinusoidal output voltage (AC voltage) ➔ 5.

A CTL converter integrates the DC capacitors into the valve. The valve consists of series-connected voltage cells that can produce a sinusoidal voltage ➔ 6. The greater the number of cells connected in series, the more sinusoidal the waveform. A CTL converter valve for the DolWin1 HVDC transmission project is shown in figure 3 page 25.

5 Voltage and current in a switch-type VSC valve with PWM

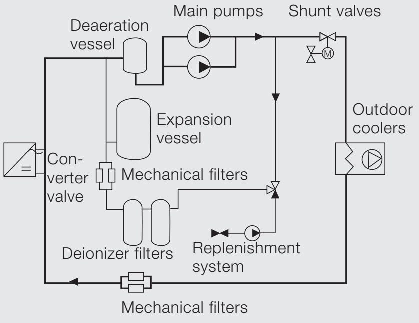


6 Voltage output of a CTL-type converter with seven voltage cells in series connection



7 StakPak IGBT used in ABB's VSC valves

8 Overview of a typical valve cooling system



9 Typical skid-based modularized redundant cooling system

In this project, one valve consists of thirty-six voltage cells.

The modular design concept for valves is found in both switch and CTL types. ABB's VSC valves use StakPak IGBTs ➔ 7. These switching modules create an internal short circuit should they fail, making them similar to thyristors. This function allows a current to continue to conduct through a faulty IGBT device without calling for an external bypass circuit (as is the case for other IGBT types). The decreased deployment of components at high potential can therefore augment the valve's availability, reliability and compactness. StakPak follows the conventional press-pack design advantages such as better cooling and robust mechanical module structure [3].

Valve cooling

The purpose of the cooling system is to dissipate the power losses generated in the valves. Coolant fluid is circulating through the heat sink in close contact with the semiconductors. This efficiently transports heat away from the device to be cooled through heat exchangers using either air or a secondary circuit. The liquid in the closed-valve cooling system is continuously passed through a de-ionizing system to keep its conductivity low.

A typical valve cooling system is shown in ➔ 8 and ➔ 9.

Jonatan Danielsson
ABB Power Systems, Grid Systems
Raleigh, NC, United States
jonatan.danielsson@us.abb.com

Baoliang Sheng
ABB Power Systems, Grid Systems
Ludvika, Sweden
baoliang.sheng@se.abb.com

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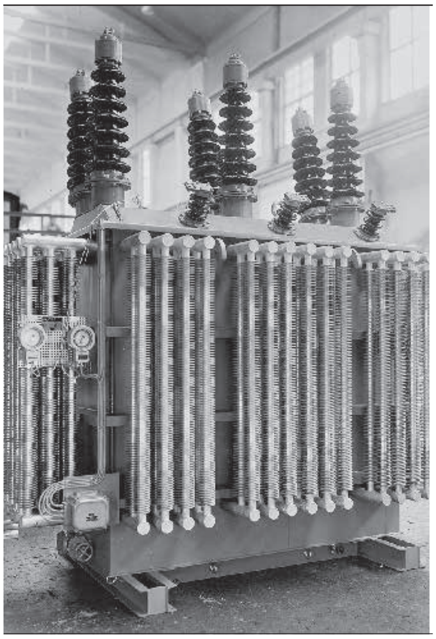
Converter transformers

A 60-year journey

1 An early converter transformer



MATS BERGLUND – ABB's HVDC-transmission transformer technology has evolved from the 1954 Gotland link → 1. ABB's predecessor company, ASEA, broke new ground with its 400 kV DC technology used in the 1,000 MW CU project (Coal Creek Station to Underwood, ND, United States) in 1977. The company asserted its undisputed technology leadership with the Itaipu (Brazil) project of 1982 (3,150 MW / 600 kV DC). This was to be a cornerstone in HVDC converter-transformer history. To realize this record-breaking milestone, ASEA built on the knowledge it accumulated delivering high power transformers to the booming AC-networks during the 1970s.

It was not until the end of the 1990s that anything close to Itaipu would be attempted in terms of transmission power. The next records were set by transmission projects in China: The first two major HVDC links were from the Three Gorges hydropower station to the load centers in eastern China, for which ABB was a key supplier.

A diversification of HVDC-transmission configurations into the Light and Classic variants started at the end of the 1990s. The thyristor-based HVDC Classic has built on its strengths –

2 The function of the HVDC converter transformer

Voltage and dielectric separation

In all HVDC systems (regardless of the converter topology) the HVDC converter transformer serves as an interconnection between the AC grid and the converter valve. Besides converting AC voltage and current to a level suitable for the converter valve, the HVDC converter transformer fulfills additional roles in the HVDC system. For many converter topologies (HVDC Classic and asymmetric HVDC Light®) the most important function of the transformer is to keep the DC-voltage offset created by the converter valve out of the AC network. This results in AC and DC stress being superimposed in the winding of the transformer.

Power and voltage regulation

The HVDC converter transformers is an integral part of the control of the HVDC system, both from an active and reactive power perspective. Compared with other transformers, the HVDC converter transformer often displays a large regulation range – a consequence of its role as an integrated regulating function of the HVDC system.

Short-circuit current limitation and system properties

In the early days of converter valves, a key feature of the transformers was to provide an impedance to limit the short-circuit current to the semiconductor valve. As the capability of semiconductors grew, this property lessened in importance. The transformer still fulfills basic functions in enabling correct interaction between the HVDC transmission and the AC network.

3 Design aspects for the HVDC-converter transformer

High power, high voltage and DC

HVDC converter transformers are among the largest transformers in terms of power, voltage and complexity. On top of this come the requirements dictated by the need to handle DC voltages.

Impact from current harmonics

For some applications, the load current seen by the transformers is not perfectly smooth. This implies extra care for the thermal dimensioning of the HVDC converter transformer as well as its accessories, bushings and tap changers.

Reactive loading

For HVDC transformers, reactive power capability of the complete transmission is translated into the transformer's ability to handle the reactive load.

Short-circuit-like duty

The mercury-arc valves of the early HVDC days sometimes "backfired," subjecting the transformers to a condition close to short circuit. Apparently, the ABB design was sufficiently robust as there is no history of short-circuit incidents – but this was not formally proven until 2007 when ABB short-circuit tested an HVDC converter transformer for the first time.

4 HVDC transformer configurations

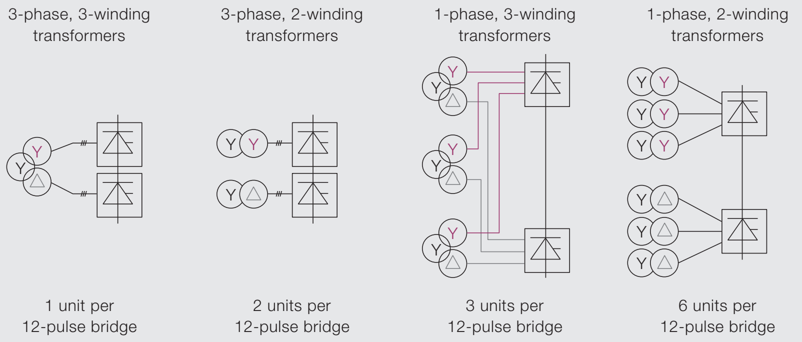
All HVDC systems need transformers, but how these are arranged can vary quite substantially between projects depending on the specification of the project. In their basic forms, each pole of an HVDC Classic system needs to be fed by six phases of transformers while HVDC Light needs a three-phase supply.

The HVDC-transformer configuration of an individual project is unique to the project and determined by the sheer size of transformers in relation to the limitations in the transport infrastructure between the place of manufacture and the HVDC converter station. The main driver behind size of the converter transformer is the rated power, which is a direct consequence of HVDC-transmission power capability and the transformer topology.

For HVDC Classic, the transformer alternatives are shown below.

Typically, more transformers are needed when transmission power and transmission voltage are high. The spare transformers strategy in the converter station also plays an important role in the selection of transformer solution.

For HVDC Light, the transformer solutions possible often are limited to the choice of single-phase and three-phase transformers.



5 Project execution

Technical and scientific proficiency is one important aspect of HVDC converter transformers, but equally important is the way projects are executed and how technology is implemented. HVDC projects often need a long series of HVDC converter transformers being manufactured in a timely manner to complete the supply for an individual project. As lead times for delivery of projects are gradually reduced, this aspect becomes more and more important.

ABB has taken the lead in this important development. The deliveries to SGCC in China are examples where ABB has set industry records. In the project between Hami and Zhengzhou ABB delivered all HVDC converter transformers to the 8,000 MW, 800 kV DC mega-project in 17 months. This should be compared with the delivery times of the Three Gorges projects where the complete time schedule ranged over 36 months. These improvements could very well stem from the abundance of projects delivered: ABB was responsible for more than 50 percent of all the projects realized – far more than any of its competitors.

The ultrahigh DC-transmission voltage is highly challenging to the insulation abilities of the converter transformers.

expanding into ultrahigh transmission voltages enabling very efficient power transmission over long distances. HVDC Light, which started off as a moderate power application, has grown into a medium-power transmission system that nowadays can do what HVDC Classic could do at the end of the 1990s ➔ 2 – 5.

To understand what contemporary HVDC transmission means for the HVDC converter transformers a complete view of the technologies and their applications are given below.

HVDC transformers today

HVDC Classic has in recent years seen rapid expansion in terms of performance. HVDC Classic can now transmit up to 11,000 MW at a transmission voltage of 1,100 kV DC. This means that the transformers must have a very high power rating, and thus a substantial physical size – weighing in excess of 600 t ➔ 6.

The ultrahigh DC-transmission voltage is highly challenging to the insulation abilities of the converter transformers. These are subjected to extreme test voltages before delivery. Besides the voltage stresses often appearing in HVDC Classic, these transformers often claim superlatives in terms of power rating as well. The largest HVDC converter transformers built have single-phase power ratings in excess of 600 MVA – the largest in the world of transformers ➔ 7.

HVDC Light

HVDC Light systems share certain features with HVDC Classic systems, while others are less prominent. Depending on the system configuration, the converter transformers are sometimes exposed to a DC stress similar to that of the HVDC Classic systems, while in some system configurations they are not. The further the capability of HVDC Light advances, the greater the DC stress that the converter transformer must face ➔ 8.

A clear contrast to the HVDC Classic systems is found in the load current that the converter transformers for HVDC Light are subject to. For HVDC Light, the load current is in most cases free from current harmonics, 6 800 kV UHVDC (ultrahigh voltage direct current) converter transformer

8 Converter transformers and the spare transformer at Woodland HVDC Light® station in Ireland.

7 Power rating references

Project	Rated power	Year
Itaipu	314 MVA	1982
Quebec-New England	404 MVA	1987
Sylmar	625 MVA	2007
Rio Madeira	630 MVA	2011
Celilo upgrade	785 MVA	2014

The thyristor-based HVDC Classic has built on its strengths – expanding into ultrahigh transmission voltages enabling very efficient power transmission over long distances.

whereas in HVDC Classic the transformers must cope with the thermal stress originating from the extra losses incurred by current harmonics.

One consequence of the reactive power capability of HVDC Light is that a large portion of the load can be reactive, something that needs to be carefully considered in the transformer design.

The future

It is not only the DC voltage level on the HVDC transmission itself that is being increased. Another trend is that HVDC converter transformers will need to connect HVDC systems directly to AC networks at even higher voltages than are used today. An HVDC-transformer technology for interconnecting the highest voltage DC transmissions to 800 kV AC systems already exists and there will soon be commercial applications. Beyond this, interconnections to even higher AC voltages, such as the 1,000 kV AC networks in China, are a possibility.

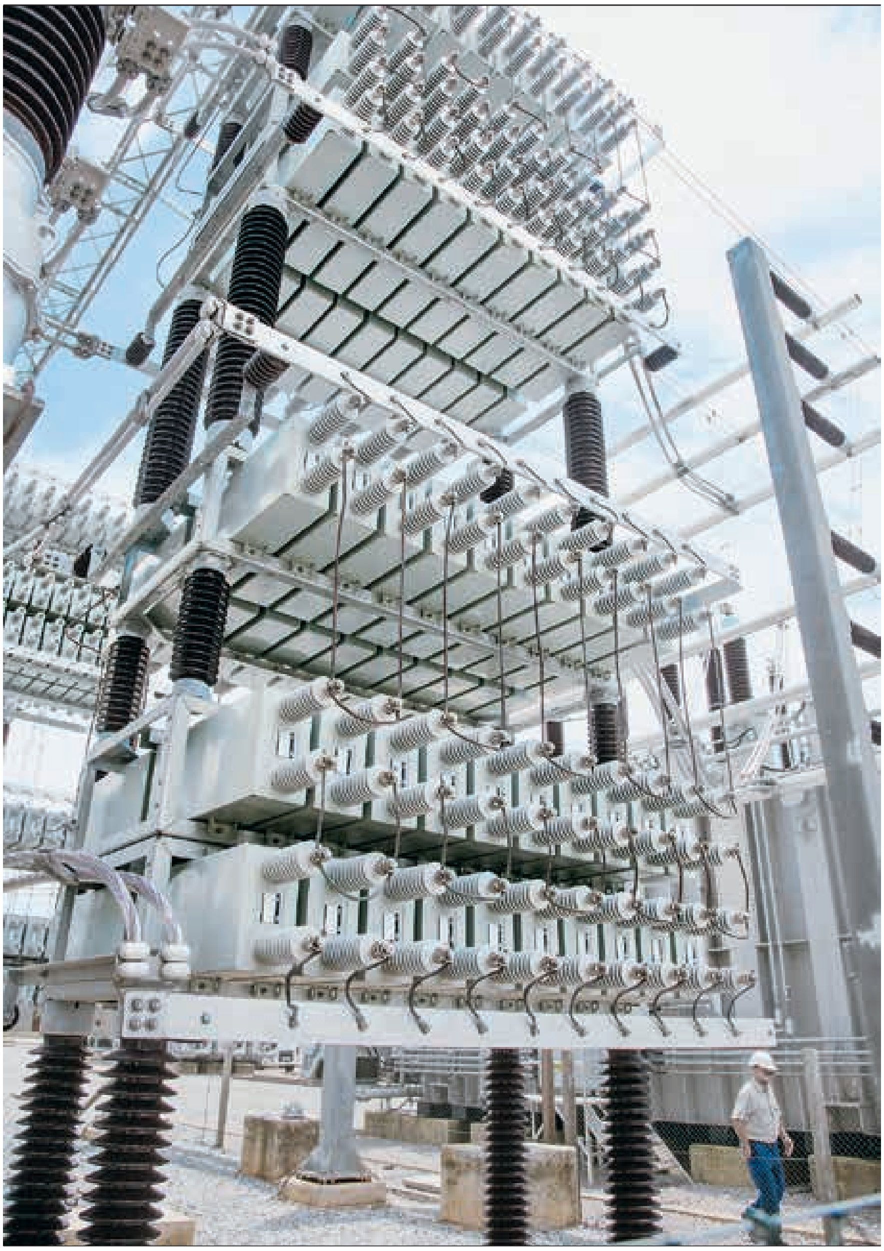
Mats Berglund
ABB Power Products
Ludvika, Sweden
mats.g.berglund@se.abb.com

Capacitors

A key component in HVDC systems

BIRGER DRUGGE, PETER HOLMBERG – Capacitors have multiple functions in HVDC systems ➔ 1. They cover aspects such as reactive power compensation, DC filtering, AC filtering and power-line carrier coupling. Capacitor technology for HVDC has gone through the various shifts in technology from impregnated mixed dielectrics (paper/film) to full-film dielectrics with highly specialized capacitor fluids. The latest technology used in HVDC Light® applications features dry solutions based on special metallized film dielectrics.

1 Capacitor bank at Porto Velho HVDC station in Brazil



ABB's technology is based on its long experience and deep understanding of specific DC phenomena such as space charges. An example of ABB's prowess is the internally fused capacitor used to maintain high levels of power quality and availability.

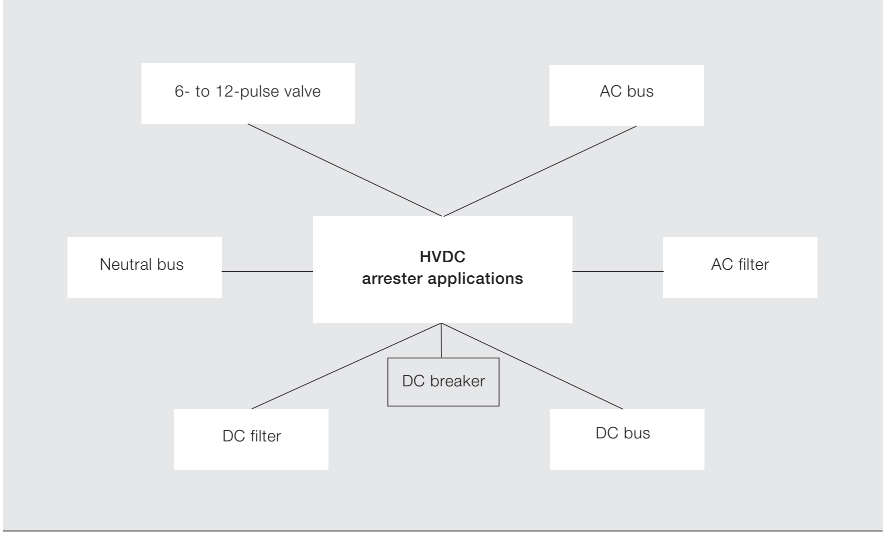
HVDC's increasing voltage levels have introduced special mechanical challenges in the design of the capacitor stacks, not the least of which concern seismic requirements.

Capacitors are part of the output filter that reduces harmonics. One challenge faced is that these harmonics generate sound in the components. Special patented sound-attenuating solutions have been developed to keep the sound level low and meet environmental requirements.

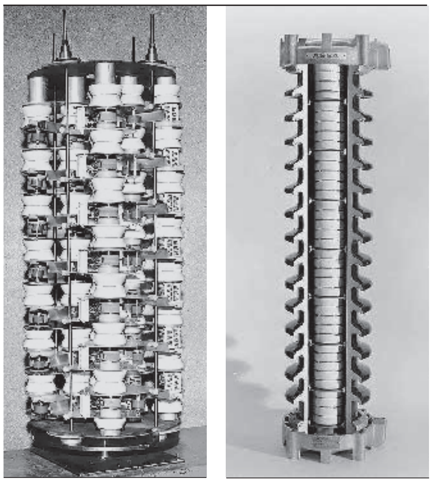
As a technology leader, ABB also drove the technology shift to dry HVDC capacitors for HVDC Light, required to handle unit voltage ratings above 150 kV. ABB's dry DC capacitor technology is based on metallized film with self-healing properties. With ABB's dry technology, customers benefit from higher availability and reduced footprint of the link, also improving the eco-aspect of the solution.

Birger Drugge
Peter Holmberg
ABB Power Products,
High Voltage Products
Ludvika, Sweden
birger.drugge@se.abb.com
peter.holmberg@se.abb.com

1 ABB's HVDC arresters



2 Comparison of gapped SiC arrester and gapless ZnO surge arrester



2a XDL 280 A surge arrester (1970s)

2b ZnO surge arrester (1980s)

Surge arresters

60 years of HVDC protection

LENNART O. STENSTROM, JAN-ERIK SJÖDIN – An HVDC station features different types of surge arresters to protect the equipment from overvoltages caused by lightning and/or switching events. In some equipment such as DC breakers, surge arresters also may form an integral part of the apparatus.

The stresses the arresters have to be designed for, compared with normal AC arresters, are characterized by, for example:

- Special voltage waveforms comprising frequency components ranging from pure DC, and power frequency to several kHz
- Very low protection levels required
- High energy demands – eg, for valve arrester, neutral-bus arresters and arresters for DC breakers
- High ambient temperature, eg, for valve arresters

The various arresters normally used in an HVDC project are shown in → 1.

Historically HVDC stations were first protected by gapped SiC surge arresters until the late 1970s when gapless ZnO surge arresters were introduced. The last generation of the gapped arresters were quite complex and comprised a vast number of components such as spark gaps, SiC blocks, grading capacitors and grading SiC resistors. The design became even more complex when parallel columns had to be used to meet high energy demands or low protection levels → 2 shows how the introduction of the ZnO material remarkably simplified the internal design of the surge arresters compared with the previous gapped HVDC arrester.

A short history of ABB (and predecessor company ASEA) HVDC surge arresters is shown in → 3 and → 5.

ABB has a number of designs for HVDC arresters optimized for thermal, electrical and mechanical stresses, safety requirements and cost depending on the application.

To date, tens of thousands of ABB HVDC arresters have been delivered worldwide with an excellent service record.

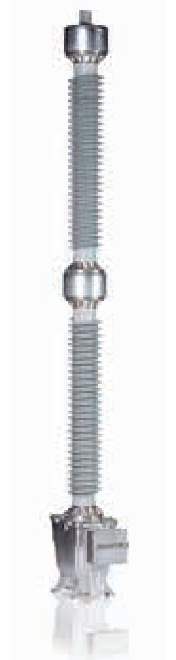
Instrument transformers – reliable metering and protection

ABB has been producing instrument transformers by the thousands for more than 70 years → 4. Their applications range from revenue metering, control, indication and relay protection. One field of application in HVDC is the use of capacitor voltage

3 Surge arrester history at ABB

Pre-1979: Gapped SiC arrester
1979: First gapless ZnO surge arrester (probably the world's first) delivered to a 250 kV HVDC station in Denmark ➔ 5a
2000: First 500 kV arrester with polymer-housing delivered to the 3GS project in China ➔ 5b
2006: First 800 kV arrester type tested and energized for a China project
2012: First 1,100 kV arrester fully type tested ➔ 5c

4 420 kV cap. volt. transf.



5 The first gapless HVDC arrester and the first 500 and 1,100 kV DC bus arresters with polymer housings

5a Gapless HVDC line arrester (1979)

5b 500 kV DC bus arrester (2000)

5c 1,100 kV DC bus arrester (2012)

ABB has been producing instrument transformers by the thousands for more than 70 years.

transformers to obtain the source voltage for converter control, as well as to obtain signals for the protection of the converter station. The output from the capacitor voltage transformers is used to trigger the thyristor valves at a certain time, based on the previous zero crossing of the AC voltage. Because even minor disturbances can be disastrous to the operation of the HVDC station, special requirements must be met for transient and frequency response.

The first capacitor voltage transformers were produced by ABB in the 1950s for delivery to the 1,000 km, 400 kV AC transmission line from Harsprånget to Hallsberg in Sweden. The electromagnetic unit in the base of a capacitor voltage transformer incorporates an inductive reactor, connected in series between the capacitive voltage divider and the high-voltage end of the primary winding, to compensate for the shift in phase angle caused by the capacitive reactance of the capacitor's voltage divider. This type of compensation allows simple construction to obtain high accuracy for high loads. However, the reactance and capacitance form a tuned circuit that gives relatively low accuracy at frequencies outside the nominal frequency.

In an HVDC application, the capacitor voltage transformer that is used to obtain the source voltage for special requirements in converter control for transient and frequency response uses an electromagnetic unit without a separate compensation reactor. For this special type, the function of the compensation reactor and the primary winding of the intermediate transformer are combined into one device. This arrangement gives a substantially increased operating frequency range, and highly improved transient response.

Lennart O. Stenstrom
Jan-Erik Sjödin
ABB Power Products,
High Voltage Products
Ludvika, Sweden
lennart.o.stenstrom@se.abb.com
jan-erik.sjodin@se.abb.com