High Voltage Direct Current Transmission –

Proven Technology for Power Exchange

Answers for energy.

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1 Why High Voltage Direct Current ?

1.1 Highlights from the High Voltage Direct Current (HVDC) History

The transmission and distribution of electrical energy started with direct current. In 1882, a 50-km-long 2-kV DC transmission line was built between Miesbach and Munich in Germany. At that time, conversion between reasonable consumer voltages and higher DC transmission voltages could only be realized by means of rotating DC machines.

In an AC system, voltage conversion is simple. An AC transformer allows high power levels and high insulation levels within one unit, and has low losses. It is a relatively simple device, which requires little maintenance. Further, a three-phase synchronous generator is superior to a DC generator in every respect. For these reasons, AC technology was introduced at a very early stage in the development of electrical power systems. It was soon accepted as the only feasible technology for generation, transmission and distribution of electrical energy.

However, high-voltage AC transmission links have disadvantages, which may compel a change to DC technology:

- Inductive and capacitive elements of overhead lines and cables put limits to the transmission capacity and the transmission distance of AC transmission links.
- This limitation is of particular significance for cables. Depending on the required transmission capacity, the system frequency and the loss evaluation, the achievable transmission distance for an AC cable will be in the range of 40 to 100 km. It will mainly be limited by the charging current.
- Direct connection between two AC systems with different frequencies is not possible.
- Direct connection between two AC systems with the same frequency or a new connection within a meshed grid may be impossible because of system instability, too high short-circuit levels or undesirable power flow scenarios.

Engineers were therefore engaged over generations in the development of a technology for DC transmissions as a supplement to the AC transmissions.

Line-Commutated Current Sourced Converters

The invention of mercury arc rectifiers in the nineteen-thirties made the design of line-commutated current sourced converters possible.

In 1941, the first contract for a commercial HVDC system was signed in Germany: 60 MW were to be supplied to the city of Berlin via an underground cable of 115 km length. The system with ± 200 kV and 150 A was ready for energizing in 1945. It was never put into operation.

Since then, several large HVDC systems have been realized with mercury arc valves.

The replacement of mercury arc valves by thyristor valves was the next major development. The first thyristor valves were put into operation in the late nineteen-seventies.

The outdoor valves for Cahora Bassa were designed with oil-immersed thyristors with parallel/series connection of thyristors and an electromagnetic firing system.

Further development went via air-insulated air-cooled valves to the air-insulated water-cooled design, which is still state of the art in HVDC valve design.

The development of thyristors with higher current and voltage ratings has eliminated the need for parallel connection and reduced the number of series-connected thyristors per valve. The development of light-triggered thyristors has further reduced the overall number of components and thus contributed to increased reliability.

Innovations in almost every other area of HVDC have been constantly adding to the reliability of this technology with economic benefits for users throughout the world.

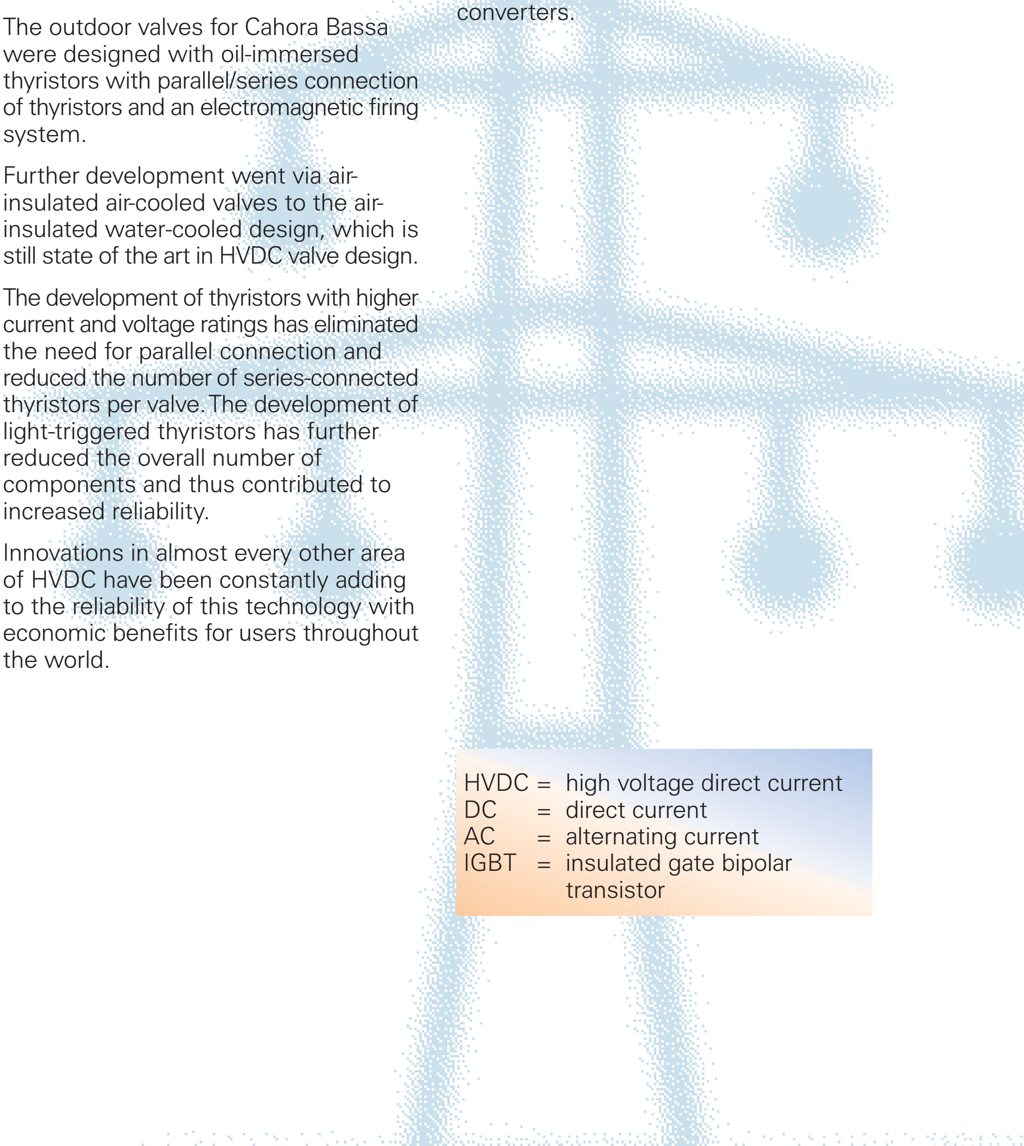
Self-Commutated Voltage Sourced Converters

Voltage sourced converters require semiconductor devices with turn-off capability. The development of Insulated Gate Bipolar Transistors (IGBT) with high voltage ratings have accelerated the development of voltage sourced converters for HVDC applications in the lower power range.

The main characteristics of the voltage sourced converters are a compact design, four-quadrant operation capability and high losses.

Siemens is offering voltage sourced converters for HVDC applications with ratings up to 250 MW under the trade name HVDC^{plus} Power Link Universal Systems.

This paper focuses upon HVDC transmission systems with high ratings, i.e. with line-commutated current sourced converters.



HVDC = high voltage direct current
DC = direct current
AC = alternating current
IGBT = insulated gate bipolar transistor

1.2 Technical Merits of HVDC

The advantages of a DC link over an AC link are:

- A DC link allows power transmission between AC networks with different frequencies or networks, which can not be synchronized, for other reasons.
- Inductive and capacitive parameters do not limit the transmission capacity or the maximum length of a DC overhead line or cable. The conductor cross section is fully utilized because there is no skin effect.

For a long cable connection, e.g. beyond 40 km, HVDC will in most cases offer the only technical solution because of the high charging current of an AC cable. This is of particular interest for transmission across open sea or into large cities where a DC cable may provide the only possible solution.

- A digital control system provides accurate and fast control of the active power flow.
- Fast modulation of DC transmission power can be used to damp power oscillations in an AC grid and thus improve the system stability.

1.3 Economic Considerations

For a given transmission task, feasibility studies are carried out before the final decision on implementation of an HVAC or HVDC system can be taken. Fig. 1-1 shows a typical cost comparison curve between AC and DC transmission considering:

- AC vs. DC station terminal costs
- AC vs. DC line costs
- AC vs. DC capitalised value of losses

The DC curve is not as steep as the AC curve because of considerably lower line costs per kilometre. For long AC lines the cost of intermediate reactive power compensation has to be taken into account.

The break-even distance is in the range of 500 to 800 km depending on a number of other factors, like country-specific cost elements, interest rates for project financing, loss evaluation, cost of right of way etc.

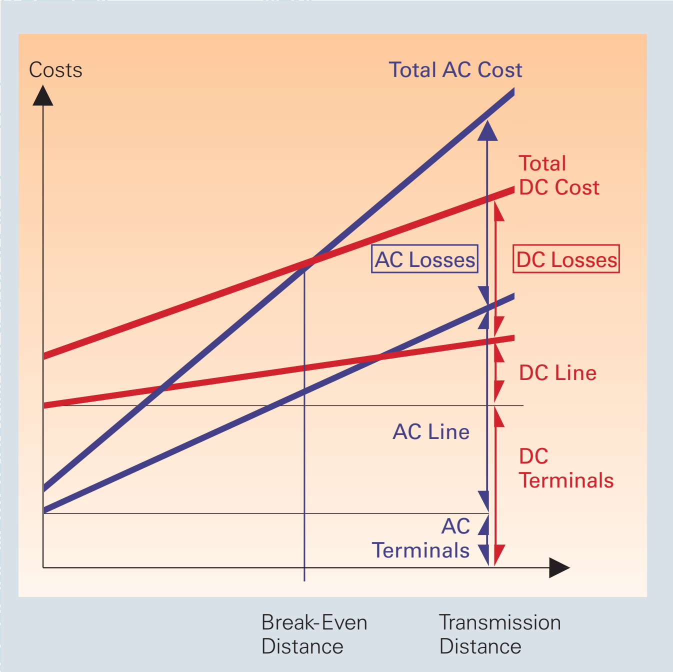


Fig. 1-1: Total cost/distance

1.4 Environmental Issues

An HVDC transmission system is basically environment-friendly because improved energy transmission possibilities contribute to a more efficient utilization of existing power plants.

The land coverage and the associated right-of-way cost for an HVDC overhead transmission line is not as high as that of an AC line. This reduces the visual impact and saves land compensation for new projects. It is also possible to increase the power transmission capacity for existing rights of way. A comparison between a DC and an AC overhead line is shown in Fig. 1-2.

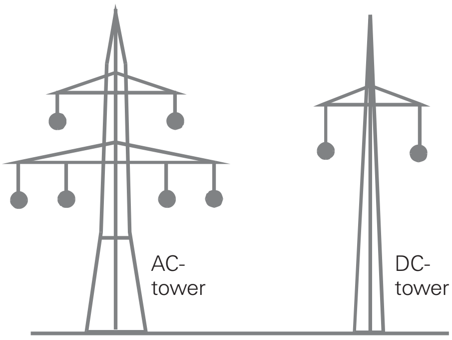


Fig. 1-2: Typical transmission line structures for approx. 1000 MW

There are, however, some environmental issues which must be considered for the converter stations. The most important ones are:

- Audible noise
- Visual impact
- Electromagnetic compatibility
- Use of ground or sea return path in monopolar operation

In general, it can be said that an HVDC system is highly compatible with any environment and can be integrated into it without the need to compromise on any environmentally important issues of today.

2 Main Types of **HVDC Schemes**

2.1 DC Circuit

The main types of HVDC converters are distinguished by their DC circuit arrangements. The following equivalent circuit is a simplified representation of the DC circuit of an HVDC pole.

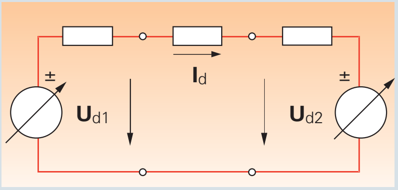


Fig. 2-1: Equivalent DC circuit

The current, and thus the power flow, is controlled by means of the difference between the controlled voltages. The current direction is fixed and the power direction is controlled by means of the voltage polarity. The converter is described in the next section.

2.2 Back-to-Back Converters

The expression Back-to-back indicates that the rectifier and inverter are located in the same station.

Back-to-back converters are mainly used for power transmission between adjacent AC grids which can not be synchronized. They can also be used within a meshed grid in order to achieve a defined power flow.

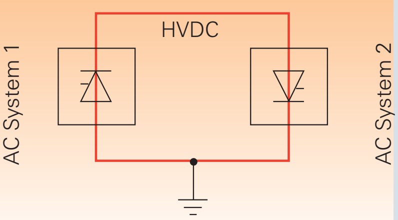


Fig. 2-2: Back-to-back converter

2.3 Monopolar Long-Distance Transmissions

For very long distances and in particular for very long sea cable transmissions, a return path with ground/sea electrodes will be the most feasible solution.

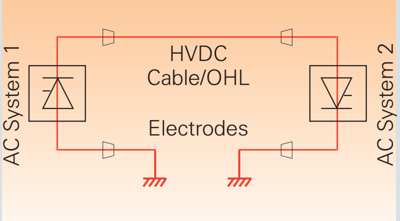


Fig. 2-4: Monopole with ground return path

In many cases, existing infrastructure or environmental constraints prevent the use of electrodes. In such cases, a metallic return path is used in spite of increased cost and losses.

Fig. 2-3: Back-to-back converter Station Vienna Southeast

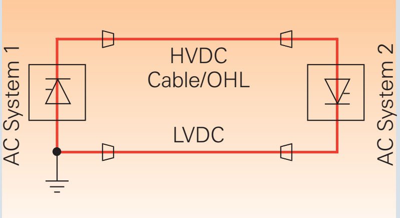


Fig. 2-5: Monopole with metallic return path

HVDC = high voltage direct current
DC = direct current
AC = alternating current
U_d = DC voltage 12-pulse
I_d = DC current
OHL = overhead line
LVDC = low voltage direct current

2.4 Bipolar Long-Distance Transmissions

A bipole is a combination of two poles in such a way that a common low voltage return path, if available, will only carry a small unbalance current during normal operation.

This configuration is used if the required transmission capacity exceeds that of a single pole. It is also used if requirement to higher energy availability or lower load rejection power makes it necessary to split the capacity on two poles.

During maintenance or outages of one pole, it is still possible to transmit part of the power. More than 50% of the transmission capacity can be utilized, limited by the actual overload capacity of the remaining pole.

The advantages of a bipolar solution over a solution with two monopoles are reduced cost due to one common or no return path and lower losses. The main disadvantage is that unavailability of the return path with adjacent components will affect both poles.

2.4.1 Bipole with Ground Return Path

This is a commonly used configuration for a bipolar transmission system. The solution provides a high degree of flexibility with respect to operation with reduced capacity during contingencies or maintenance.

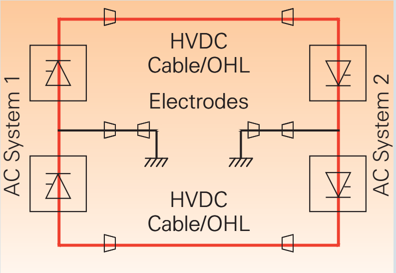


Fig. 2-6: in bipolar balanced operation (normal)

Upon a single-pole fault, the current of the sound pole will be taken over by the ground return path and the faulty pole will be isolated.

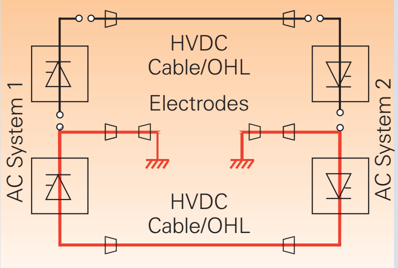


Fig. 2-7: in monopolar ground return operation (converter pole or OHL outage)

Following a pole outage caused by the converter, the current can be commutated from the ground return path into a metallic return path provided by the HVDC conductor of the faulty pole.

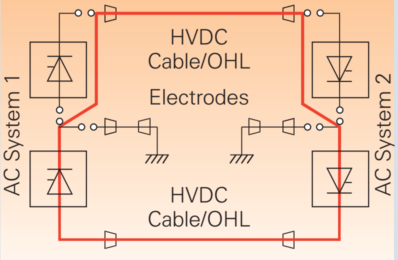


Fig. 2-8: in monopolar metallic return operation (converter pole outage)

2.4.2 Bipole with Dedicated Metallic Return Path for Monopolar Operation

If there are restrictions even to temporary use of electrodes, or if the transmission distance is relatively short, a dedicated LVDC metallic return conductor can be considered as an alternative to a ground return path with electrodes.

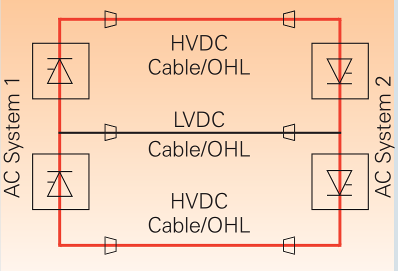


Fig. 2-9: in bipolar balanced operation (normal)

2.4.3 Bipole without Dedicated Return Path for Monopolar Operation

A scheme without electrodes or a dedicated metallic return path for monopolar operation will give the lowest initial cost.

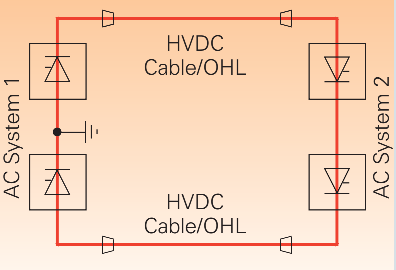


Fig. 2-10: in bipolar balanced operation (normal)

Monopolar operation is possible by means of bypass switches during a converter pole outage, but not during an HVDC conductor outage.

A short bipolar outage will follow a converter pole outage before the bypass operation can be established.

3 Converter **Theory**

3.1 Bridge Circuit Function

Current flows through the valves when the voltage between the anode and cathode is positive. For the valve to commutate the current, there must be a positive potential (voltage), and the thyristor must have firing pulses. In the reverse direction, i.e. when the potential between anode and cathode is negative, a firing pulse has no effect. The flow of current in a valve ends when the voltage between anode and cathode becomes negative. The instant when current begins to flow through a valve, or to commutate from one valve to another, can be delayed by postponing the firing. This method permits the average value of the outgoing voltage of the rectifier to be changed. The firing pulses are generated by synchronizing the network using an electronic control device. These pulses can be displaced from their ”natural firing“ point, which is the point where the two phase voltages intersect. The method of firing-pulse displacement is called phase control.

The angle between the time at which the valve voltage becomes positive and the firing time (start of commutation) is referred to as the firing delay. Fig. 3-2 shows that for a firing delay of 90°, the average voltage equals zero. i.e. the positive and negative areas of the curve – voltage against time – cancel each other out. No active power flows through the converter.

When the firing delay is greater than 90°, the negative voltage/time areas dominate, and the polarity of the average direct voltage changes. Due to physical reasons, the direction of the current does not change. (The thyristor valves conduct current only in one direction.) When the direction of energy flow is reversed, the delivery changes to the supply side. The rectifier becomes an inverter which delivers energy to the AC network.

The average value of the direct voltage as a function of the firing delay is given by:

$U_{di\alpha}$ = 1.35 * U_L * cos α
U_L = secondary side line voltage
α = firing angle
γ = extinction angle

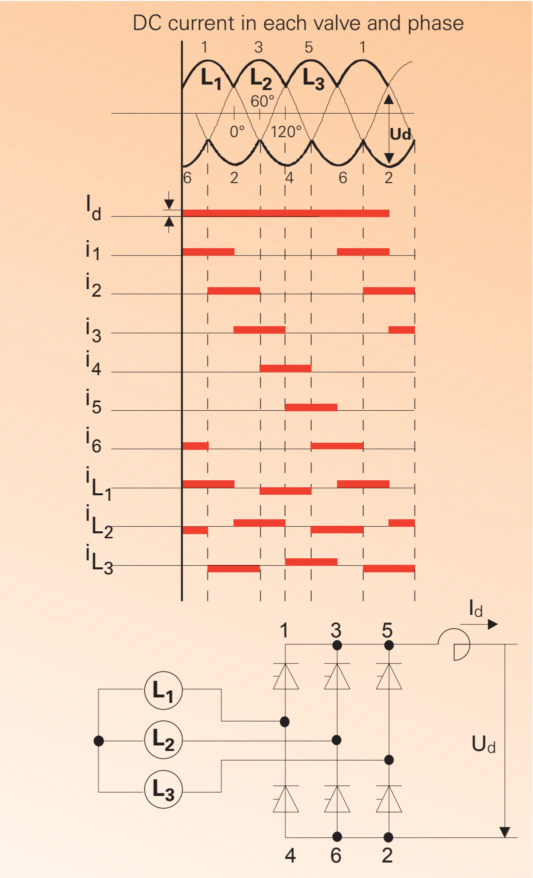


Fig. 3-1: Six-pulse converter bridge

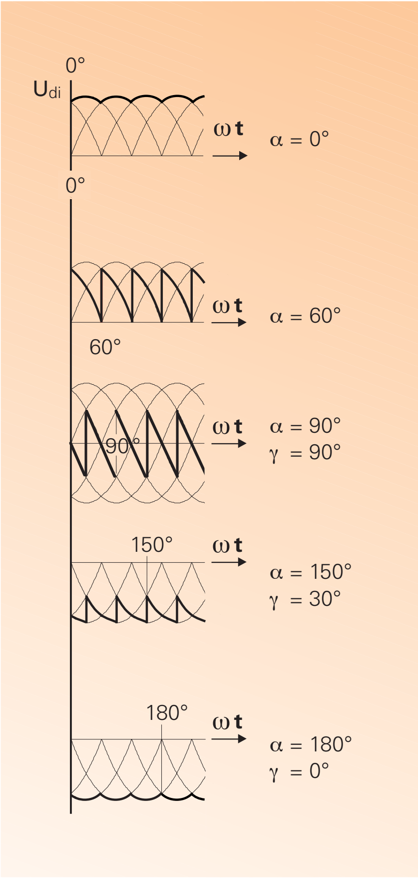


Fig. 3-2: DC voltage of bridge converter as a function of α

3.2 12-Pulse Group and Converter Transformer

HVDC converters are usually built as 12-pulse circuits. This is a serial connection of two fully controlled 6-pulse converter bridges and requires two 3-phase systems which are spaced apart from each other by 30 electrical degrees. The phase difference effected to cancel out the 6-pulse harmonics on the AC and DC side.

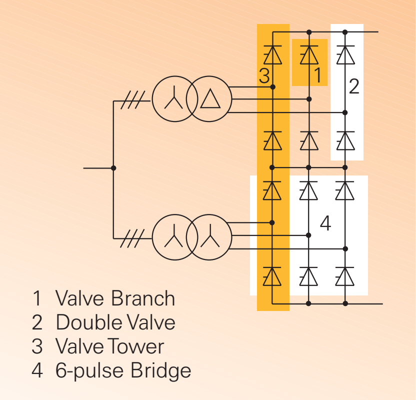


Fig. 3-3: Arrangement of the valve branches in a 12-pulse bridge

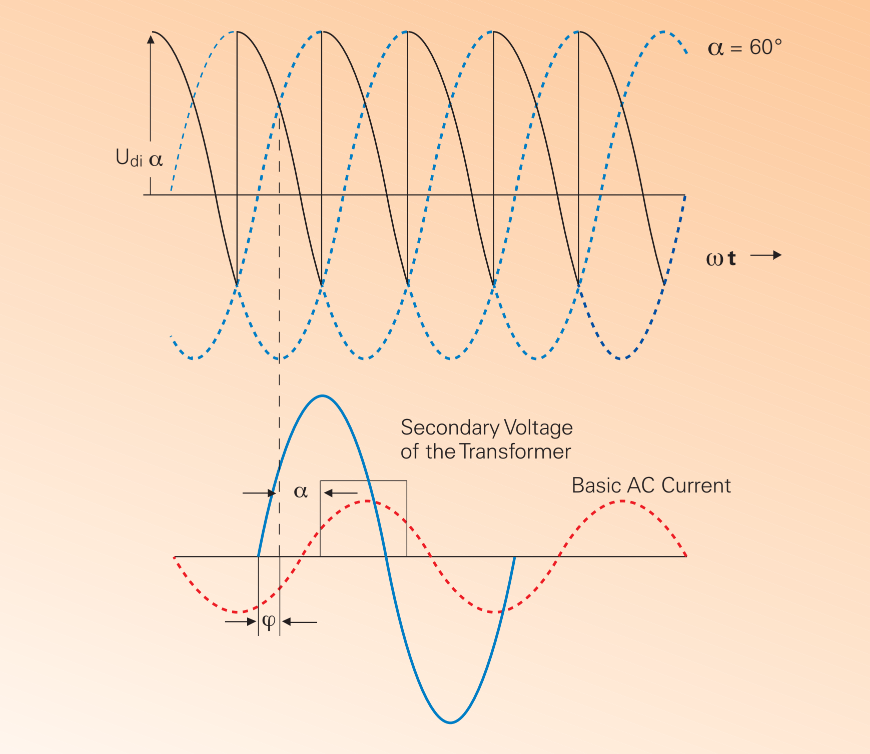


Fig. 3-4:
Current displacement with angle control

HVDC DC Circuit

$U_{dN} = P_{dN\ Rec}/I_{dN}$

U_{dN} => nominal DC voltage 12-pulse

I_{dN} => nominal DC current

P_{dNRec} => nominal DC active power at the rectifier

3.3 Reactive Power as a Function of Load

The curve of reactive power demand of an HVDC station with changing active power P can be calculated from equation:

$Q = P * \tan [\arccos (\cos \alpha - d_x)]$

In Fig. 3-5, the reactive power demand of a converter is presented under three different control methods.

If the terminal DC voltage U_d and the firing angle α (or the extinction angle γ of an inverter) are held constant, curve (1) will be obtained. If, however, U_v is held constant (U_{di} = const regulation), a linear curve such as (2) is obtained. The power of a converter can also be changed when the (nominal) current is held constant by varying the DC voltage. Curve (3) shows the reactive power demand for this control method. It is important to note that the entire area between curves (1) and (3) is available for reactive power control. Each point within this area can be set by the selection of firing angles α and ß (or γ).

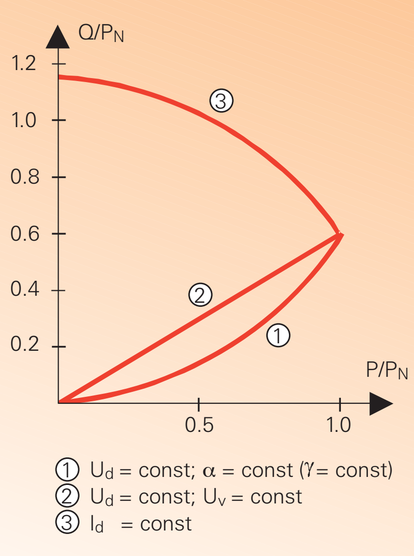


Fig. 3-5:
Reactive power demand of an HVDC converter

d_x = relative inductive voltage drop
U_v = valve voltage
U_d = DC voltage 12-pulse
α = firing angle
ß = 180°-α
γ = extinction angle

3.4 Reactive Power Control

The possibility of electronic reactive power control as demonstrated in the preceding section is used only to a very limited degree in HVDC technology. This is due to economic reasons. Both control reactive power and commutation reactive power are increased by the reduction of the DC voltage and the corresponding increase of current. However, load losses increase with the square of the current. For this reason, application is limited to the light loads where the necessary filter circuits produce a considerable overcompensation for the reactive power required by the converter.

Fig. 3-6 depicts the reactive power control of the Dürnrohr HVDC link. In this system, a compensation to ±60 Mvar was specified. Compliance with the Q limit is achieved by load-dependent switching of a capacitor bank and one of the two high-pass filters. Electronic reactive power is used only in the light load range. Normally, there is a difference between the connect and disconnect points of the reactive power elements. This provides a "switching hysteresis" which prevents too many switching operations or even a "pumping".

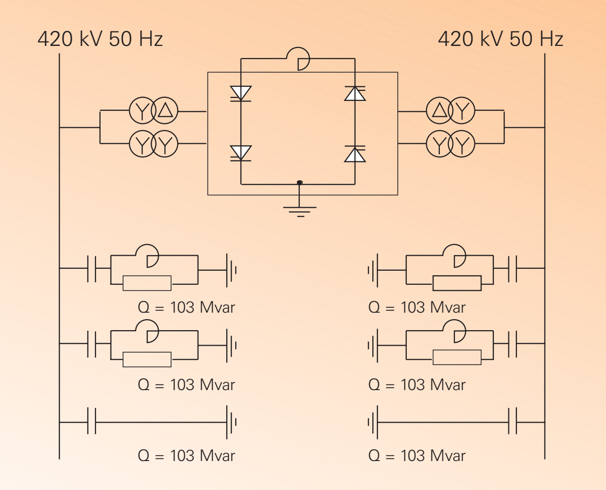
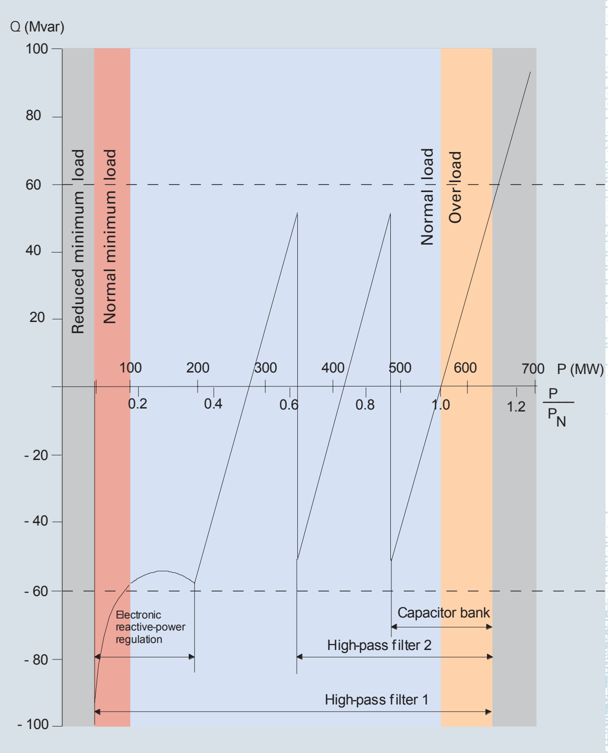


Fig. 3-6: Reactive-power compensation and control of an HVDC back-to-back link



Reactive-Power Balance

U_{AC} in p.u. (AC bus voltage)

– cap. + ind	reactive-power converter		reactive-power AC filters		reactive-power reactors		reactive-power capacitors
$Q_{Network} =$	$+ Q_{Conv}$	$-$	$Q_{FK} * U_{AC}^2$	$+$	$Q_L * U_{AC}^2$	$-$	$Q_C * U_{AC}^2$

Principle Arrangement of an **HVDC Transmission Project**

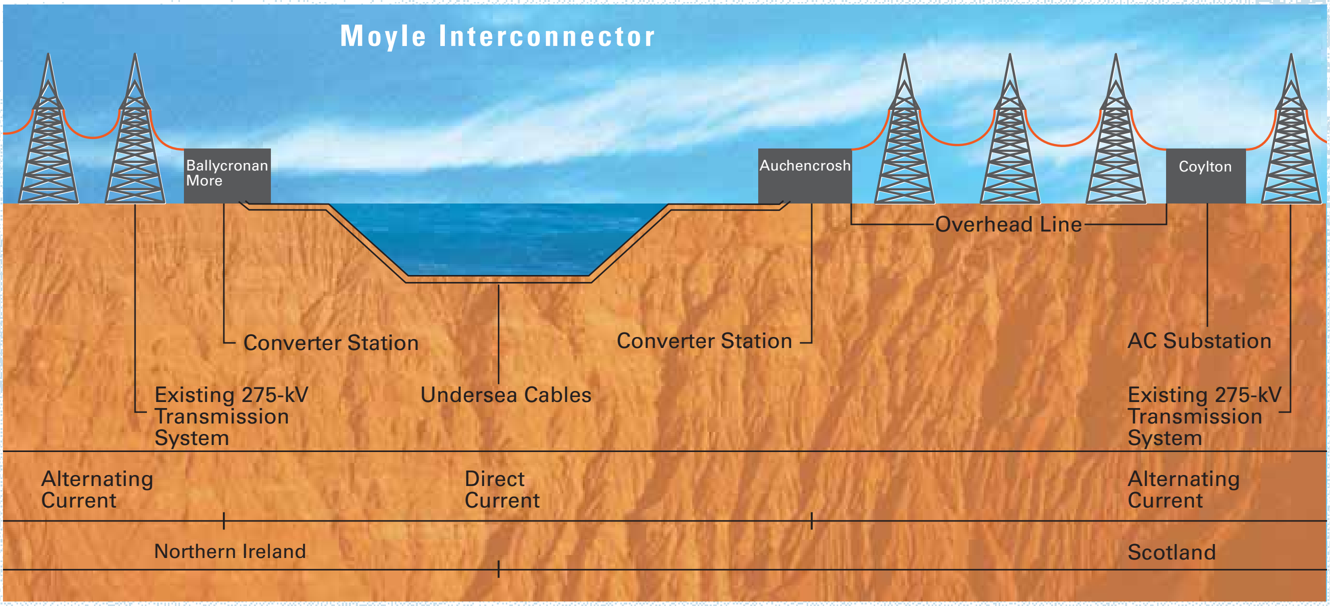
The Principle Arrangement of an HVDC Transmission Project is reflected on the Moyle Interconnector project. The HVDC stations between Northern Ireland and Scotland are operating with the following highlights:

- Direct light triggered thyristor valves for the complete HVDC system, with 1872 thyristors in total, with 20% better reliability and all valve components free from oil.
- Triple tuned AC filter in both stations.
- Unmanned stations, fully automatic remote operation and automatic load schedule operation.
- Hybrid optical ohmic shunt for DC current measuring unit.
- Low noise station design for:
  - AC filter capacitor and reactors
  - converter transformer
  - converter valve water cooling system
  - DC hall with smoothing reactor
- Station design for DC see/land cable with integrated return conductor and fibre optic cable for control and communication.

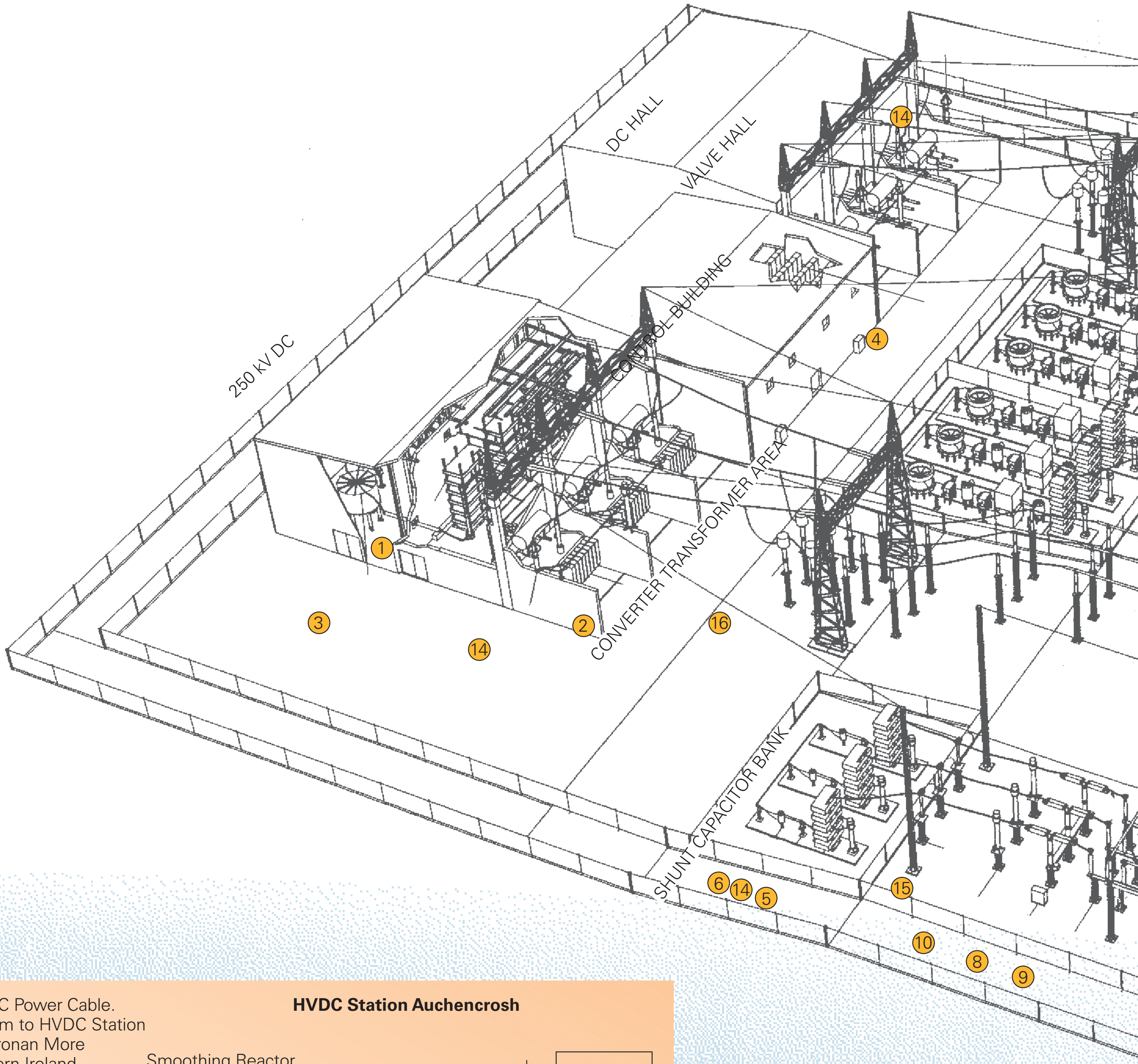
Date of contract	09/99
Delivery period	27 months

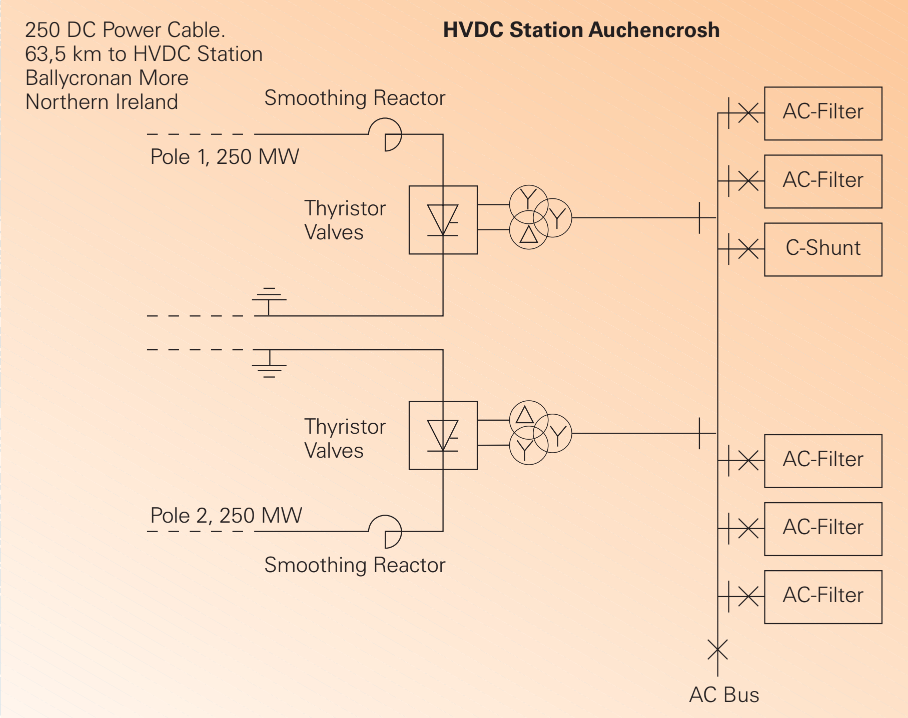
System Data

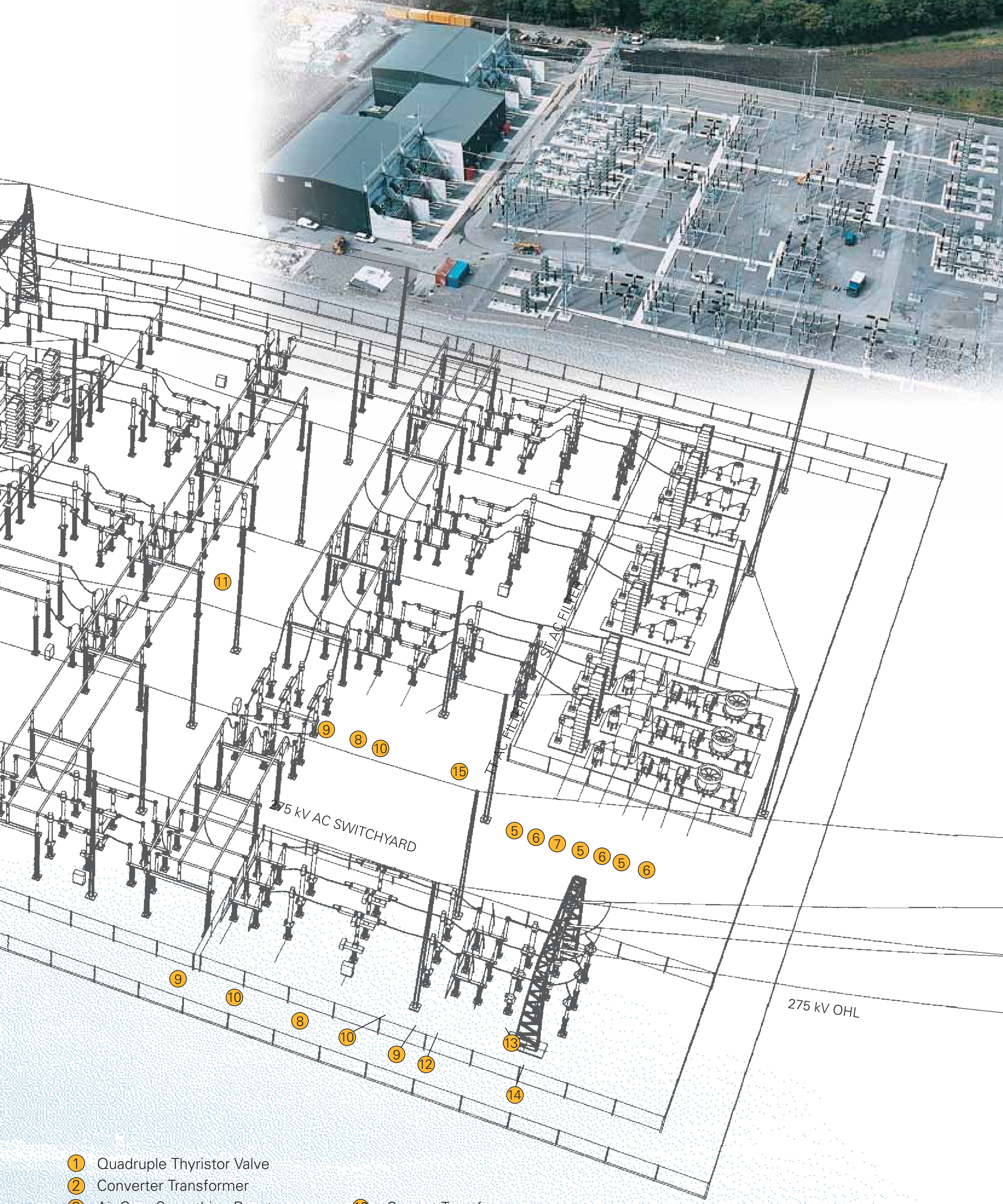
Transmission capacity	2 x 250 MW
System voltages	250 kV DC 275 kV AC
Rated current	1000 A
Transmission distance	63.5 km



4 Principle Arrangement of an **HVDC Transmission Project**







① Quadruple Thyristor Valve
② Converter Transformer
③ Air Core Smoothing Reactor
④ Control Room and Control Cubicle
⑤ AC Filter Capacitor
⑥ AC Filter Reactor
⑦ AC Filter Resistor
⑧ Circuit Breaker
⑨ Disconnector
⑩ Current Transformer
⑪ Voltage Transformer
⑫ Combined Current-Voltage Transformer
⑬ Capacitive Voltage Transformer
⑭ Surge Arrester
⑮ Earthing Switch
⑯ AC PLC Filter

5 Main Components

Components

Siemens is a leading supplier of HVDC systems all over the world. Our components are exceeding the usual quality standards and are system-tailored to the needs of the grid.

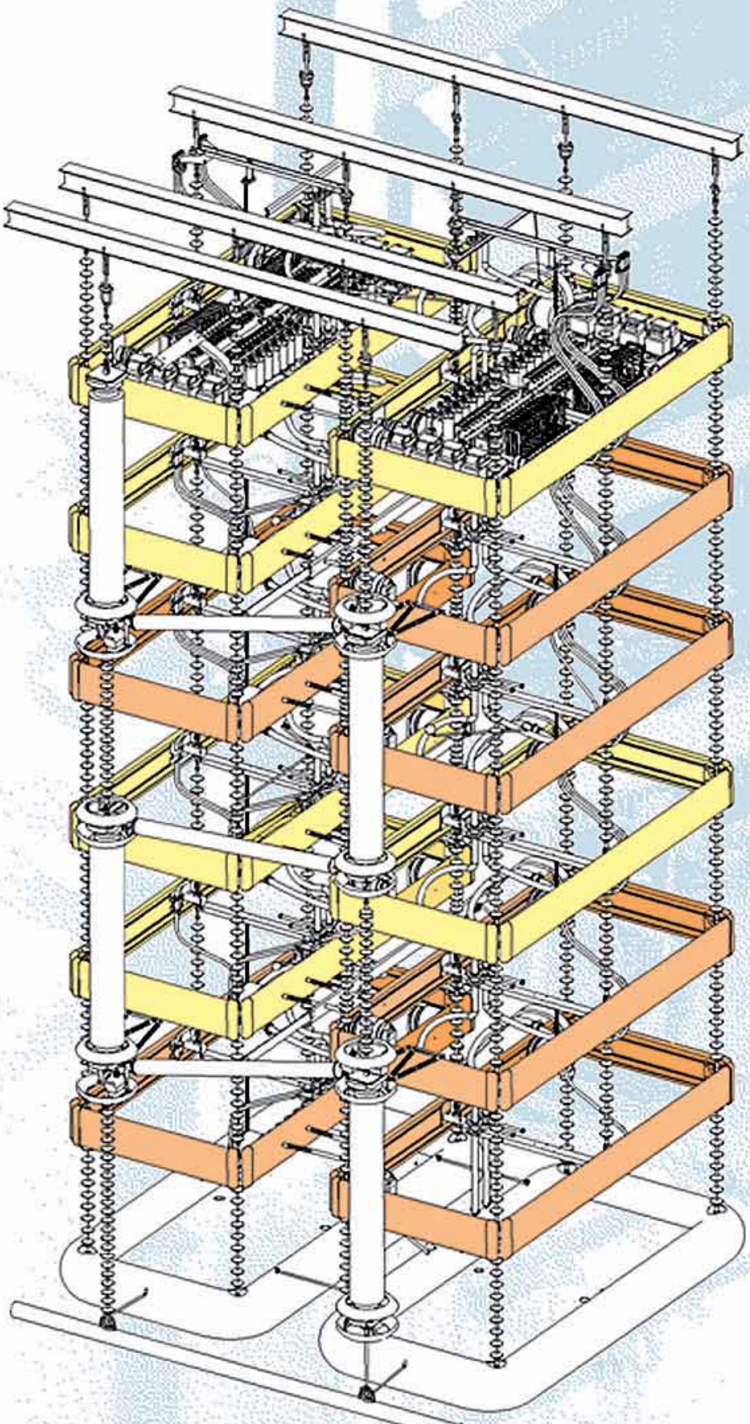
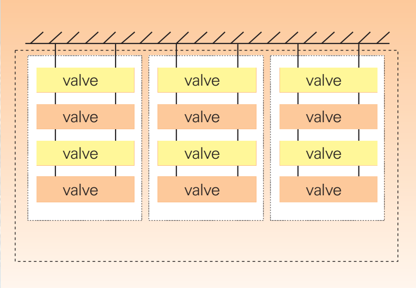


Fig. 5.1-2: General arrangement of a 500 kV MVU (valve tower)

5.1.1 Introduction

The thyristor valves make the conversion from AC into DC and thus are the central component of any HVDC converter station. The thyristor valves are of the indoor type and air-insulated. Siemens has more than 30 years experience in the development and manufacturing of thyristor valves and has maintained the technical leadership by introducing new innovative concepts such as the corrosion-free water cooling and the self-protecting direct-light-triggered thyristor. This directly reflects in the high reliability of these valves.



12-pulse group

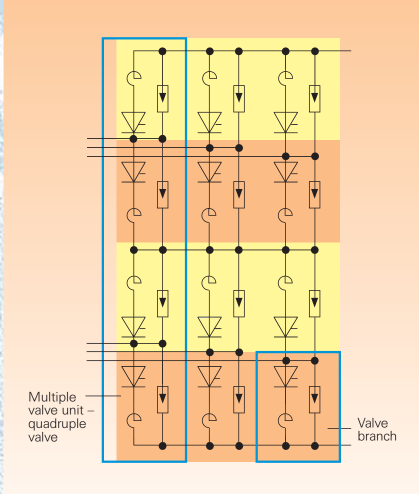


Fig. 5.1-1: Principle circuit diagram of a 12-pulse group consisting of three quadruple valves

5.1.2 Valve Design

The modular concept of the Siemens thyristor valves permits different mechanical setups to best suit each application: single, double, quadruple valves or complete six-pulse bridges – either free – standing or suspended from the building structure.

For seismic requirement reasons which exist in some regions of the world, the standard Siemens valves for long distance transmission are suspended from the ceiling of the valve hall. The suspension insulators are designed to carry the weight and additional loads originating for example from an unbalanced weight distribution due to insulator failure, an earthquake or during maintenance. Connections between modules (piping of cooling circuit, fibre optic ducts, buswork, and suspension insulator fixtures) are flexible in order to allow stress-free deflections of the modules inside an MVU (multiple valve unit) structure. Figure 5.1-2 shows a typical quadruple valve tower for a 500 kV DC system. Each valve is made up of three modules. Four arresters, each related to one valve, are located on one side of the valve tower. Ease of access for maintenance purposes, if required, is another benefit of the Siemens valve design. By varying the number of thyristors per module and the number of modules per valve, the same design can be used for all transmission voltages that may be required.

5.1 Thyristor **Valves**

5.1.3 Thyristor Development

Thyristors are used as switches and thus the valve becomes controllable. The thyristors are made of highly pure monocrystalline silicon. The high speed of innovation in power electronics technology is directly reflected in the development of the thyristor. The high performance thyristors installed in HVDC plants today are characterized by silicon wafer diameters of up to 5" (125 mm), blocking voltages up to 8 kV and current carrying capacities up to 4 kA DC. Thus no parallel thyristors need to be installed in today's HVDC systems for handling the DC current. The required DC system voltages are achieved by a series connection of a sufficient number of thyristors.

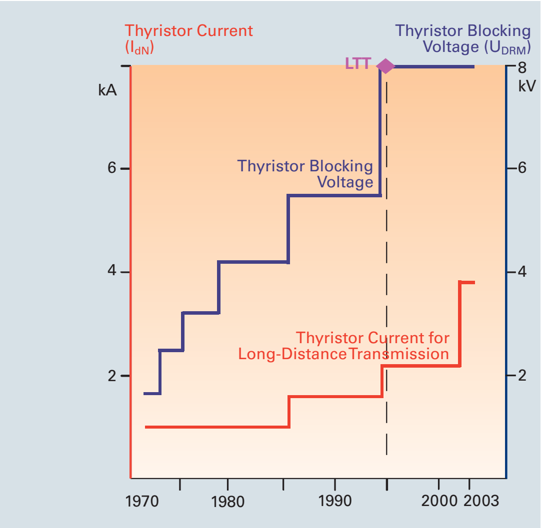


Fig. 5.1-3: Thyristor development

Cu = Copper
Si = Silicon
Mo = Molybdenum
LTT = Light-triggered thyristors
ETT = electrically triggered thyristors

5.1.4 LTT (Light-Triggered Thyristor)

It has long been known that thyristors can be turned on by injecting photons into the gate instead of electrons. The use of this new technology reduces the number of components in the thyristor valve by up to 80%. This simplification results in increased reliability and availability of the transmission system. With LTT technology, the gating light pulse is transmitted via a fibre optic cable through the thyristor housing directly to the thyristor wafer and thus no elaborate electronic circuits and auxiliary power supplies are needed at high potential. The required gate power is just 40 mW. The forward overvoltage protection is integrated in the wafer. Further benefits of the direct light triggering are the unlimited black start capability and the operation during system undervoltage or system faults without any limitations. In case of electrically triggered thyristors (ETT), this is only possible if enough firing energy is stored long enough on the thyristor electronics.

Direct light-triggered thyristors with integrated overvoltage protection (LTT) is now a proven technology and the Siemens standard. It was implemented successfully for the first time in 1997 (Celilo Converter Station of the Pacific Intertie). It shows excellent performance and no thyristor failures or malfunction of the gating system have been recorded. BPA has emphasized its confidence in this technology in 2001 by awarding Siemens the contract to replace all mercury arc valves with direct-light-triggered thyristor valves. Furthermore, this valve technology is used for the Moyle Interconnector (2 x 250 MW), which went into service in 2001 and is on contract for the 3000-MW, ± 500-kV Guizhou-Guangdong system.

Monitoring of the thyristor performance is achieved by a simple voltage divider circuit made from standard off-the-shelf resistors and capacitors; monitoring signals are transmitted to ground potential through a dedicated set of fibre optic cables as for the ETT. However, all electronic circuits needed for the evaluation of performance are now located at ground potential in a protected environment, further simplifying the system. The extent of monitoring is the same as for the ETT.
It can be expected that this technology will become the industry standard in HVDC thyristor valves of the 21st century, paving the way towards maintenance-free thyristor valves.

Fig. 5.1-4: Valve module with direct-light-triggered thyristor

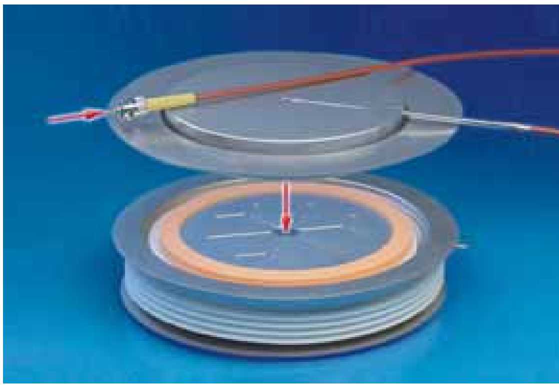


Fig. 5.1-5: Silicon wafer and housing of a direct-light-triggered thyristor

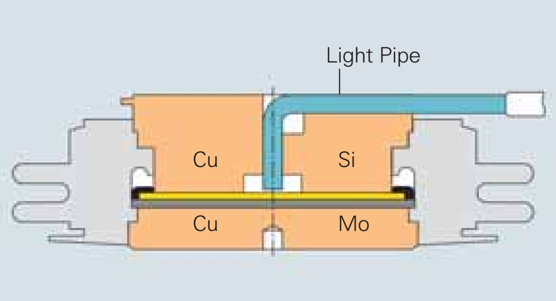


Fig. 5.1-6: The optical gate pulse is transmitted directly to the thyristor wafer

5.1.5 Valve Cooling

Siemens has used the parallel water cooling principle for more than 25 years. No corrosion problems have ever been encountered.

The thyristors are stacked in the module with a heat sink on either side. The water connection to the heat sinks can be designed in parallel or series as shown in figure 5.1-7. The parallel cooling circuit provides all thyristors with the same cooling water temperature. This allows a better utilization of the thyristor capability. Siemens makes use of this principle, which offers the additional advantage that electrolytic currents through the heat sinks – the cause for electrolytic corrosion – can be avoided by placing grading electrodes at strategic locations in the water circuit. Siemens water cooling also does not require any de-oxygenizing equipment.

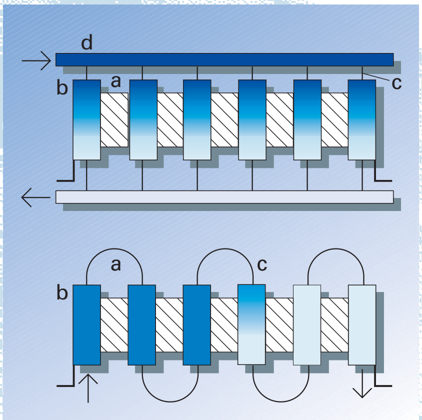


Fig. 5.1-7: Piping of module cooling circuit – parallel flow (top); series flow (bottom)
a) thyristor; b) heat sink; c) connection piping; d) manifold

5.1.6 Flame Resistance

A lot of effort has been invested by Siemens to minimize the fire risk:

- All oil has been eliminated from the valve and its components. Snubber capacitors and grading capacitors use SF_6 as a replacement for impregnating oil.
- Only flame-retardant and self-extinguishing plastic materials are used.
- A wide separation between the modular units ensures that any local overheating will not affect neighbouring components.
- Careful design of the electrical connections avoids loose contacts.

The past has shown that Siemens HVDC installations have never been exposed to a hazardous valve fire. The tests performed on actual components and samples in the actual configuration as used in the valve indicate that the improved design is indeed flame-retardant and the risk of a major fire following a fault is extremely low or even non-existent.

Fig. 5.1-8: Converter valves
Sylmar HVDC station, Los Angeles, USA

5.2 **Converter** Transformer

Siemens supplies transformers which meet all requirements concerning power, voltage, mode of operation, low noise level, connection techniques, type of cooling, transport and installation. They also comply with special national design requirements.

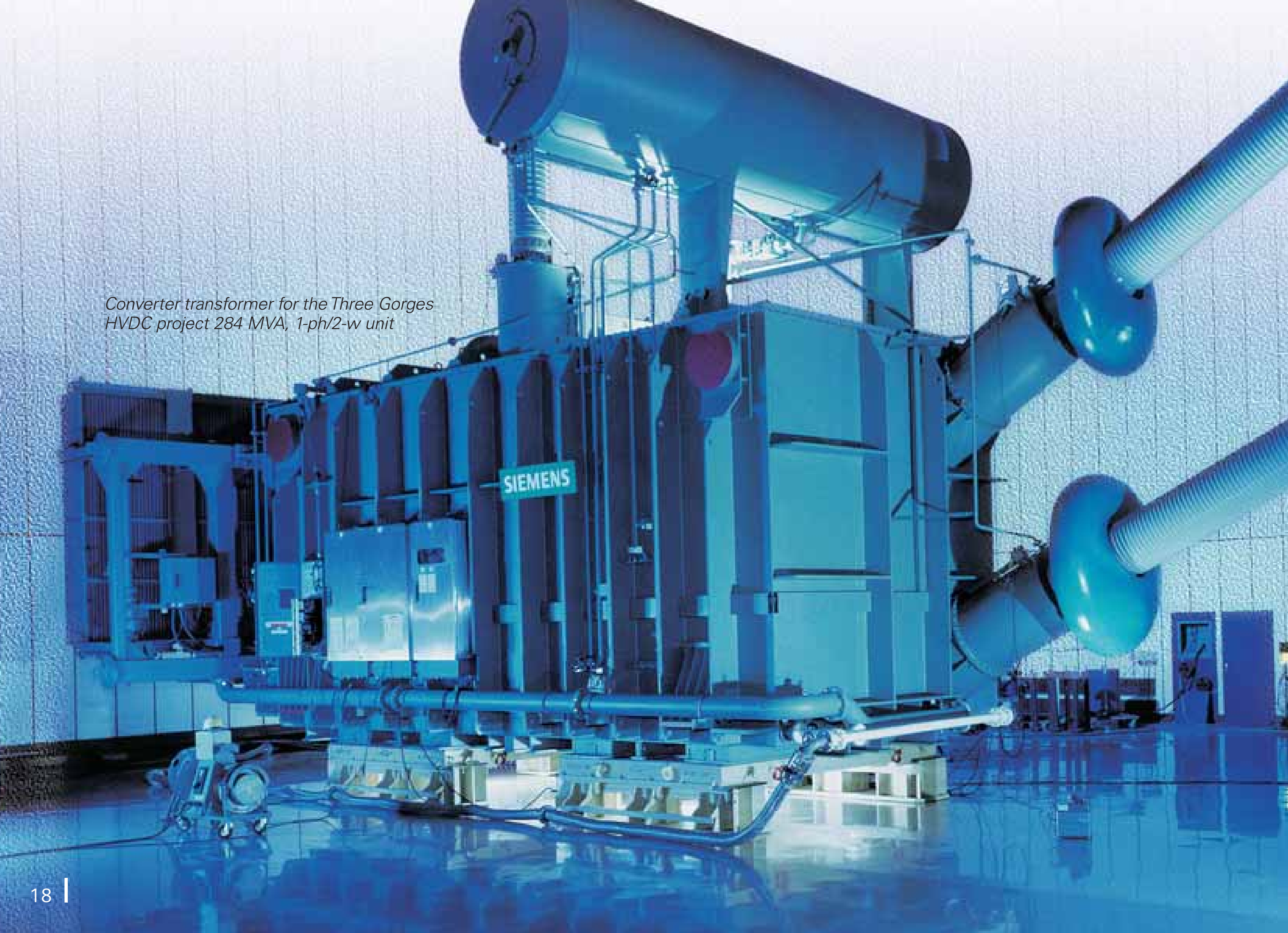
All over the world, power transformers from Nuremberg enjoy a great reputation. What the Nuremberg plant manufactures reflects today's state of the art and testifies to the highest levels of quality and reliability. Our quality management system is certified to DIN 9001, the world's most stringent standard. Our accredited test laboratories likewise meet the latest specifications.

Project: Tian Guang
HVDC bipolar long-distance transmission

P_N *= 2 x 900 MW*
U_d *= ± 500 kV*

Transformers:
S_N *= 354/177/177 MVA*
1-ph/3-w unit
U_{AC} *= 220 kV*

Fig. 5.2-1: Converter transformer for the Tian Guang HVDC project during type test



Converter transformer for the Three Gorges HVDC project 284 MVA, 1-ph/2-w unit

5.2.1 Functions of the HVDC Converter Transformer

The converter transformers transform the voltage of the AC busbar to the required entry voltage of the converter.

The 12-pulse converter requires two 3-phase systems which are spaced apart from each other by 30 or 150 electrical degrees. This is achieved by installing a transformer on each network side in the vector groups Yy0 and Yd5.

At the same time, they ensure the voltage insulation necessary in order to make it possible to connect converter bridges in series on the DC side, as is necessary for HVDC technology. The transformer main insulation, therefore, is stressed by both the AC voltage and the direct voltage potential between valve-side winding and ground. The converter transformers are equipped with on-load tap-changers in order to provide the correct valve voltage.

Transformer Rating

$S_{\text{Trafo Rec (6-pulse)}} = \sqrt{2} * I_{dN} * U_{\text{sec Rec}}$

I_{dN}	nominal DC current
$U_{\text{sec Rec}}$	Transformer-voltage valve side (Rectifier)

$S_{\text{Trafo Inv (6-pulse)}} = \sqrt{2} * I_{dN} * U_{\text{sec Inv}}$

$U_{\text{sec Inv}}$	Transformer voltage valve side (inverter)

5.2.2 Transformer Design Variations

There are several aspects which play a role in selecting the transformer design:

Transportation Weight and Dimensions

In systems of high power, weight can be an important consideration, in particular where transportation is difficult. The relative transportation weights of the 4 major design types are approximately as follows:

Single-phase – two-winding transformer	1
Single-phase – three-winding transformer	1.6
Three-phase – two-winding transformer	2.2
Three-phase – three-winding transformer	3.6

The transport dimension and the weight of the converter transformer depends on the limitations for street, railway and shipping, especially in the case of bridges, subways and tunnels.

5.2.3 HVDC Makes Special Demands on Transformers

HVDC transformers are subject to operating conditions that set them apart from conventional system or power transformers. These conditions include:

- Combined voltage stresses
- High harmonics content of the operating current
- DC premagnetization of the core

The valve windings which are connected to the rectifier and the converter circuit are subject to the combined load stress of DC and AC voltage. Added to this stress are transient voltages from outside caused by lightning strikes or switching operations.

The high harmonics content of the operating current results from the virtually quadratic current blocks of the power converter. The odd-numbered harmonics with the ordinal numbers of 5, 7, 11, 13, 17 … cause additional losses in the windings and other structural parts.

5.2.4 Main Components of the Converter Transformer

Core

HVDC transformers are normally single-phase transformers, whereby the valve windings for the star and delta connection are configured either for one core with at least two main limbs or separately for two cores with at least one main limb, depending on the rated power and the system voltage. Appropriately sized return limbs ensure good decoupling for a combined arrangement of windings.

The quality of the core sheets, the lamination of the sheets, and the nominal induction must all conform to special requirements covering losses, noise level, over-excitation, etc. Special attention must be paid to the DC premagnetization of the core due to small asymmetries during operation and stray DC currents from the AC voltage network. The effects of DC premagnetization must be compensated by appropriate design and manufacturing efforts (e.g. additional core cooling ducts, avoidance of flux pinching in the core sheet).

Windings

The large number of parameters concerning transport limitations, rated power, transformer ratio, short-circuit voltage, and guaranteed losses require significant flexibility in the design of windings.

In concentric winding arrangements, star or delta valve windings lying directly on the core have proven optimal in many cases. The line winding, normally with a tapped winding, is then mounted radial outside this core configuration.

The valve windings with high insulation levels and a large portion of current harmonics make particular demands on the design and the quality of the winding manufacturing. Together with its pressboard barriers, each limb set, including a valve, an overvoltage and a tapped winding, forms a compact unit, which is able to cope with the demand made by voltage stress, loss dissipation, and short-circuit withstand capability.

Tank

The unconventional tank design in HVDC transformers result from the following requirements:

- The valve-side bushing should extend into the valve hall
- The cooling system is mounted on the opposite side to facilitate rapid transformer exchange

For HVDC transformers with delta and star valve winding in one tank, the valve bushing must be arranged so that their ends conform to the geometry of the thyristor valve towers. This frequently leads to very high connection heights and the need to mount the oil expansion tank at a significant height.

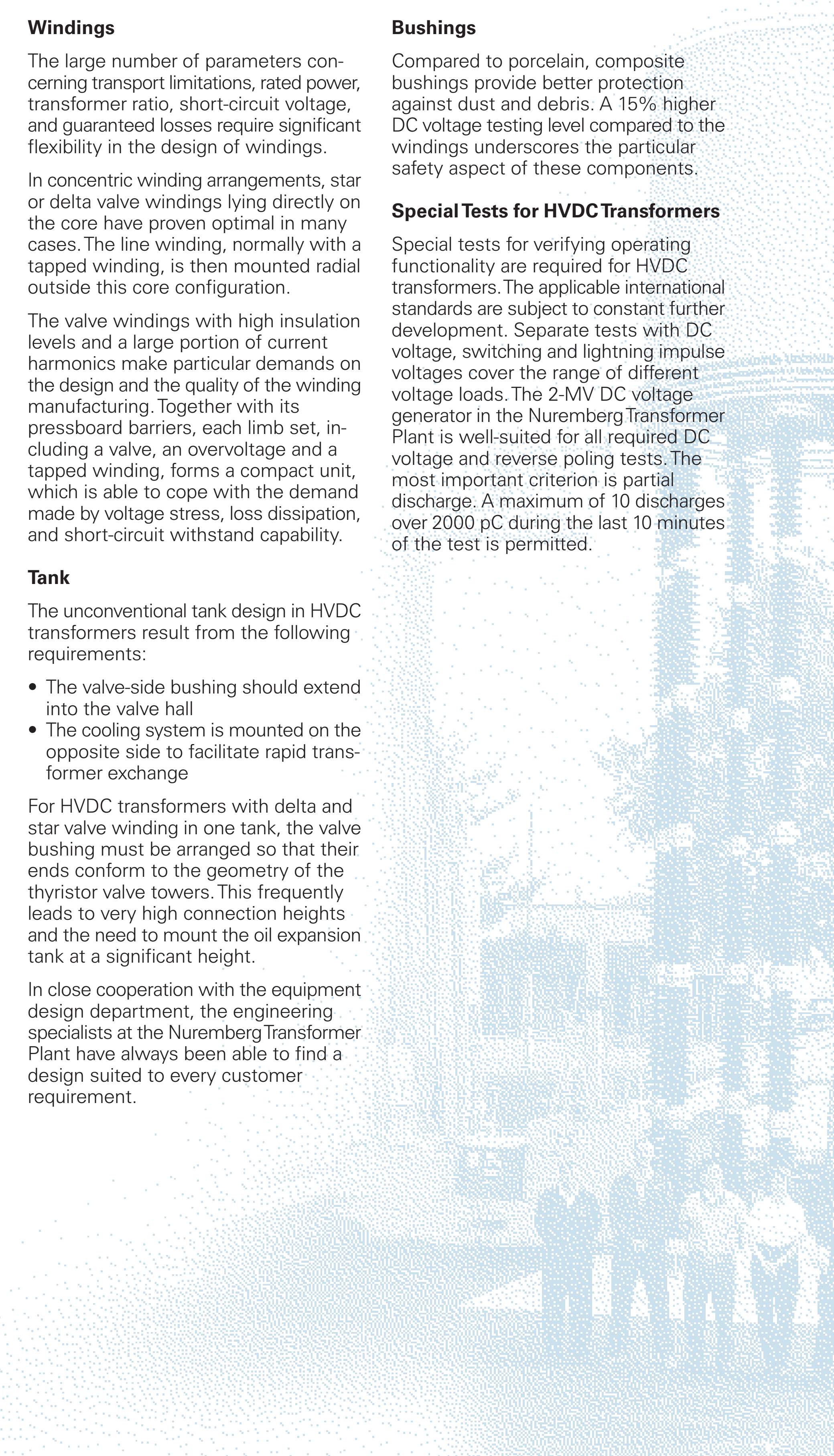
In close cooperation with the equipment design department, the engineering specialists at the Nuremberg Transformer Plant have always been able to find a design suited to every customer requirement.

Bushings

Compared to porcelain, composite bushings provide better protection against dust and debris. A 15% higher DC voltage testing level compared to the windings underscores the particular safety aspect of these components.

Special Tests for HVDC Transformers

Special tests for verifying operating functionality are required for HVDC transformers. The applicable international standards are subject to constant further development. Separate tests with DC voltage, switching and lightning impulse voltages cover the range of different voltage loads. The 2-MV DC voltage generator in the Nuremberg Transformer Plant is well-suited for all required DC voltage and reverse poling tests. The most important criterion is partial discharge. A maximum of 10 discharges over 2000 pC during the last 10 minutes of the test is permitted.



5.3.1 Functions of the Smoothing Reactor

- Prevention of intermittent current
- Limitation of the DC fault currents
- Prevention of resonance in the DC circuit
- Reducing harmonic currents including limitation of telephone interference

Prevention of intermittent current

The intermittent current due to the current ripple can cause high over-voltages in the transformer and the smoothing reactor. The smoothing reactor is used to prevent the current interruption at minimum load.

Limitation of the DC fault current

The smoothing reactor can reduce the fault current and its rate of rise for commutation failures and DC line faults.

This is of primary importance if a long DC cable is used for the transmission. For an overhead line transmission, the current stress in valves is lower than the stress which will occur during valve short circuit.

Prevention of resonance in the DC circuit

The smoothing reactor is selected to avoid resonance in the DC circuit at low order harmonic frequencies like 100 or 150 Hz. This is important to avoid the amplification effect for harmonics originally from the AC system, like negative sequence and transformer saturation.

Reducing harmonic currents including limitation of telephone interference

Limitation of interference coming from the DC overhead line is an essential function of the DC filter circuits. However, the smoothing reactor also plays an important role to reduce harmonic currents acting as a series impedance.

5.3.2 Sizing of the smoothing Reactor

While the current and voltage rating of the smoothing reactor can be specified based on the data of the DC circuit, the inductance is the determining factor in sizing the reactor. Taking all design aspects above into account, the size of smoothing reactors is often selected in the range of 100 to 300 mH for long-distance DC links and 30 to 80 mH for back-to-back stations.

5.3.3 Arrangement of the Smoothing Reactor

In an HVDC long-distance transmission system, it seems quite logical that the smoothing reactor will be connected in series with the DC line of the station pole. This is the normal arrangement. However in back-to-back schemes, the smoothing reactor can also be connected to the low-voltage terminal.

5.3.4 Reactor Design Alternatives

There are basically two types of reactor design:

- Air-insulated dry-type reactors
- Oil-insulated reactors in a tank

The reactor type should be selected taking the following aspects into consideration:

- Inductance
- Costs
- Maintenance and location of spare units
- Seismic requirements

An advantage of the dry-type reactor is that maintaining spare units (to the extent necessary) is not very expensive because they usually consist of several partial coils. However for very large inductances it is possible to have more than one unit and it could be a problem if much space is not available.

In high seismic regions, setting them on post-insulators or on an insulating platform is a possible problem. Oil-insulated smoothing reactors are then the preferred solution.

The oil-insulated reactor is economical for very high power ($I_d^2 * L_{dr}$). It is the best option for regions with high seismic requirements.

One bushing of the oil-insulated smoothing reactor penetrates usually into the valve hall, while the other bushing is normally in a vertical position. For the air-insulated dry-type smoothing reactor, a wall bushing is needed to connect with the valves.

The wall bushing in composite design is the state-of-the-art technology which provides superior insulation performance.

Fig. 5.3-1: Oil-insulated smoothing reactor – Three Gorges project

- *Inductance: 270 mH*
- *Rated voltage: 500 kV DC*
- *Rated current: 3000 A DC*

Fig. 5.3-2: Air-insulated smoothing reactor – Tian Guang project

- *Inductance: 150 mH*
- *Rated voltage: 500 kV DC*
- *Rated current: 1800 A DC*

5.4 Harmonic Filters

The filter arrangements on the AC side of an HVDC converter station have two main duties:

- to absorb harmonic currents generated by the HVDC converter and thus to reduce the impact of the harmonics on the connected AC systems, like AC voltage distortion and telephone interference
- to supply reactive power for compensating the demand of the converter station

Each filter branch can have one to three tuning frequencies. Figure 5.4.1-1 shows different harmonic filter types with their impedance frequency characteristics.

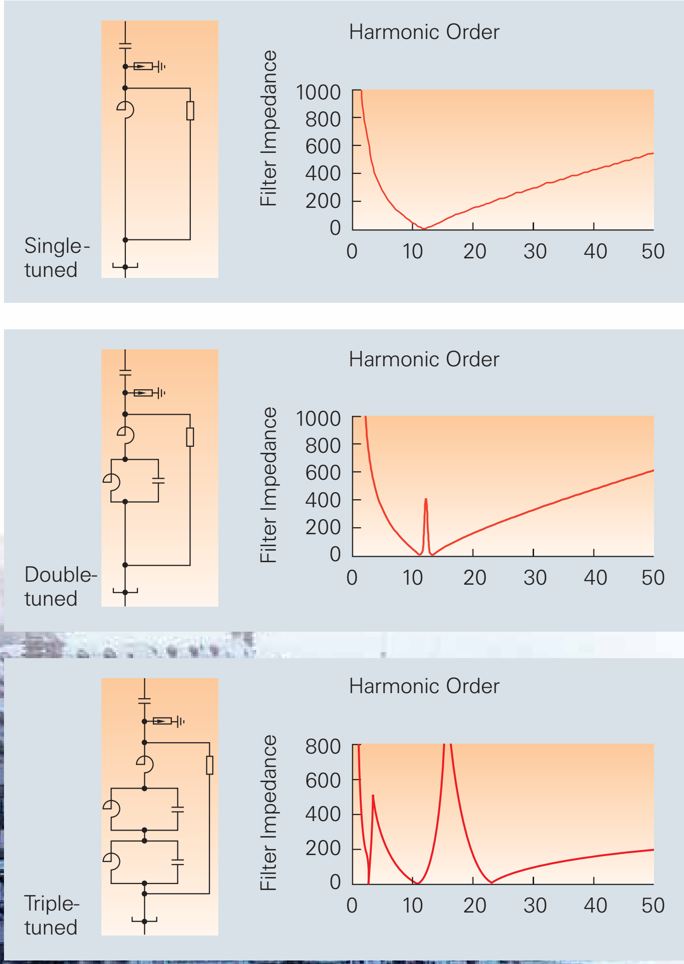


Fig. 5.4.1-1: Different harmonic filter types

Fig. 5.4.1-2: AC filters and capacitor banks of Gezhouba/Shanghai

5.4.1.1 Design Criteria for AC Filters

Reactive Power Requirements

The reactive power consumption of an HVDC converter depends on the active power, the transformer reactance and the control angle. It increases with increasing active power. A common requirement to a converter station is full compensation or overcompensation at rated load. In addition, a reactive band for the load and voltage range and the permitted voltage step during bank switching must be determined. These factors will determine the size and number of filter and shunt capacitor banks.

Harmonic Performance Requirements

HVDC converter stations generate characteristic and non-characteristic harmonic currents. For a twelve-pulse converter, the characteristic harmonics are of the order n = (12 * k) ± 1 (k = 1,2,3 ...). These are the harmonic components that are generated even during ideal conditions, i.e. ideal smoothing of the direct current, symmetrical AC voltages, transformer impedance and firing angles. The characteristic harmonic components are the ones with the highest current level, but other components may also be of importance. The third harmonic, which is mainly caused by the negative sequence component of the AC system, will in many cases require filtering.

An equivalent circuit for determination of harmonic performance is given in figure 5.4.1-3. The most commonly used criteria for harmonic performance are related to the harmonic voltage on the converter station busbar. The purpose of the filter circuit is to provide sufficiently low impedances for the relevant harmonic components in order to reduce the harmonic voltages to an acceptable level.

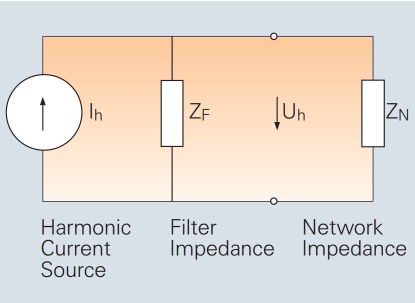


Fig. 5.4.1-3: Equivalent circuit for calculation of harmonic voltages and currents in the AC system

The acceptance criteria for the harmonic distortion depend on local conditions and regulations. A commonly used criterion for all harmonic components up to the 49th order is as follows:

D_n individual harmonic voltage distortion of order n in percent of the fundamental AC busbar voltage (typical limit 1%)

D_{rms} total geometric sum of individual voltage distortion D_n (typical limit 2%)

The BTS Telephone Interference Factor (TIF) and the CCITT Telephone Harmonic Form Factor (THFF) are determined with weighted factors in order to evaluate the voltage distortion level on the AC busbar with respect to the expected interference level in nearby analogue telephone systems. The IT product is a criterion for harmonic current injected into AC overhead lines. The criteria based on telephone interference are in many cases irrelevant, because modern digital telephone systems are insensitive to harmonic interference.

Network Impedance

The distortion level on the AC busbar depends on the grid impedance as well as the filter impedance. An open circuit model of the grid for all harmonics is not on the safe side. Parallel resonance between the filter impedance and the grid impedance may create unacceptable amplification of harmonic components for which the filters are not tuned. For this reason, an adequate impedance model of the grid for all relevant harmonics is required in order to optimize the filter design.

There are basically two methods to include the network impedance in the filter calculations:

- to calculate impedance vectors for all relevant harmonics and grid conditions
- to assume locus area for the impedance vectors

The modelling of a complete AC network with all its components is very complex and time-consuming. For this reason, the locus method is very often used. It is based on a limited number of measurements or calculations. Different locus areas for different harmonics or bands are often determined to give a more precise base for the harmonic performance calculation.

A typical locus area is shown in fig. 5.4.1-4. It is assumed that the impedance vector will be somewhere inside the perimeter of the coloured area.

The impedance vector of the filter is transformed into the Y plane for each harmonic frequency.

With both the network and the filter impedances plotted in the admittance plane, the shortest vector between the filter admittance point and the network admittance boundary gives the lowest possible admittance value for the parallel combination of the network and the filter. This value is used to determine the highest possible harmonic voltage.

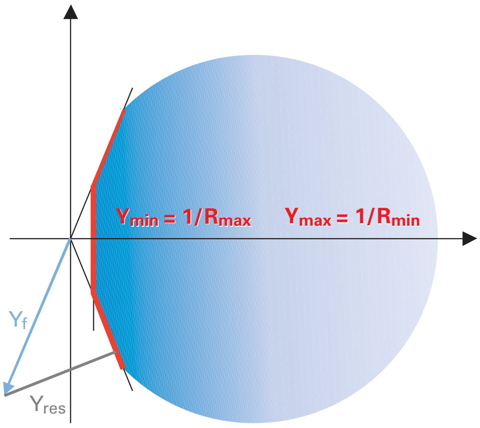


Fig. 5.4.1-4 Circle of network admittance and the resonance conditions

I_h = harmonic source current
Z_f = filter impedance
Z_N = network impedance
U_h = harmonic voltage

5.4.1 AC Harmonic Filter

The selective resonance method represents a reasonable compromise. It takes into consideration the fact that the highest voltage distortion (highest harmonic voltage) occurs with a parallel resonance between filter and AC network. It is unrealistic however, to assume that such a parallel resonance takes place at all frequencies. Normally it is sufficient to consider in the calculation of total distortion and TIF value only two maximum individual distortions from the resonance calculation. The AC network is assumed to be open for the remaining harmonic currents.

The filter calculations must reflect detuning caused by AC network frequency deviations and component parameter deviations. Production tolerances, temperature drift and failure of capacitor elements are the main contributors to parameter deviations.

Requirements to Ratings

Steady-State Calculation

The voltage and current stresses of AC filters consist of the fundamental frequency and harmonic components. Their magnitudes depend on the AC system voltage, harmonic currents, operating conditions and AC system impedances. The rating calculations are carried out in the whole range of operation to determine the highest steady-state current and voltage stresses for each individual filter component.

Transient Calculation

The objective of the transient rating calculation is to determine the highest transient stresses for each component of the designed filter arrangement. The results of the transient calculation should contain the voltage and current stresses for each component, energy duty for filter resistors and arresters, and the insulation levels for each filter component.

To calculate the highest stresses of both lightning and switching surge type, different circuit configurations and fault cases should be studied:

- **Single-Phase Ground Fault**
  The fault is applied on the converter AC bus next to the AC filter. It is assumed that the filter capacitor is charged to a voltage level corresponding to the switching impulse protective level of the AC bus arrester.
- **Switching Surge**
  For the calculation of switching surge stresses, a standard wave of 250/2500 μs with a crest value equal to the switching impulse protective level of the AC bus arrester is applied at the AC converter bus.
- **Filter Energization**
  The AC filter is assumed to be energized at the moment for the maximum AC bus peak voltage. This case is decisive for the inrush currents of AC filters.
- **Fault Recovery after Three-Phase Ground Fault**
  Various fault-clearing parameters should be investigated to determine the maximum energy stresses for AC filter arresters and resistors. The worst-case stresses are achieved if the HVDC converters are blocked after fault initiation, while the AC filters remain connected to the AC bus after fault clearing and recovery of the AC system voltage. In this case, a temporary overvoltage with high contents of non-characteristic harmonics will occur at the AC bus due to the effects of load rejection, transformer saturation and resonance between filter and AC network at low frequency.

Fig. 5.4.2-1 DC filter of Guangzhou/China

5.4.2.1 DC Filter Circuits

Harmonic voltages which occur on the DC side of a converter station cause AC currents which are superimposed on the direct current in the transmission line. These alternating currents of higher frequencies can create interference in neighbouring telephone systems despite limitation by smoothing reactors.
DC filter circuits, which are connected in parallel to the station poles, are an effective tool for combating these problems. The configuration of the DC filters very strongly resembles the filters on the AC side of the HVDC station. There are several types of filter design. Single and multiple-tuned filters with or without the high-pass feature are common. One or several types of DC filter can be utilized in a converter station.

5.4.2.2 Design Criteria for DC Filter Circuits

The interference voltage induced on the telephone line can be characterized by the following equation:

$$I_{eq} = \sqrt{\sum_{1}^{m} (H_\mu * C_\mu * I_{\mu(x)})^2}$$

$$V_{in(x)} = Z * I_{eq}$$

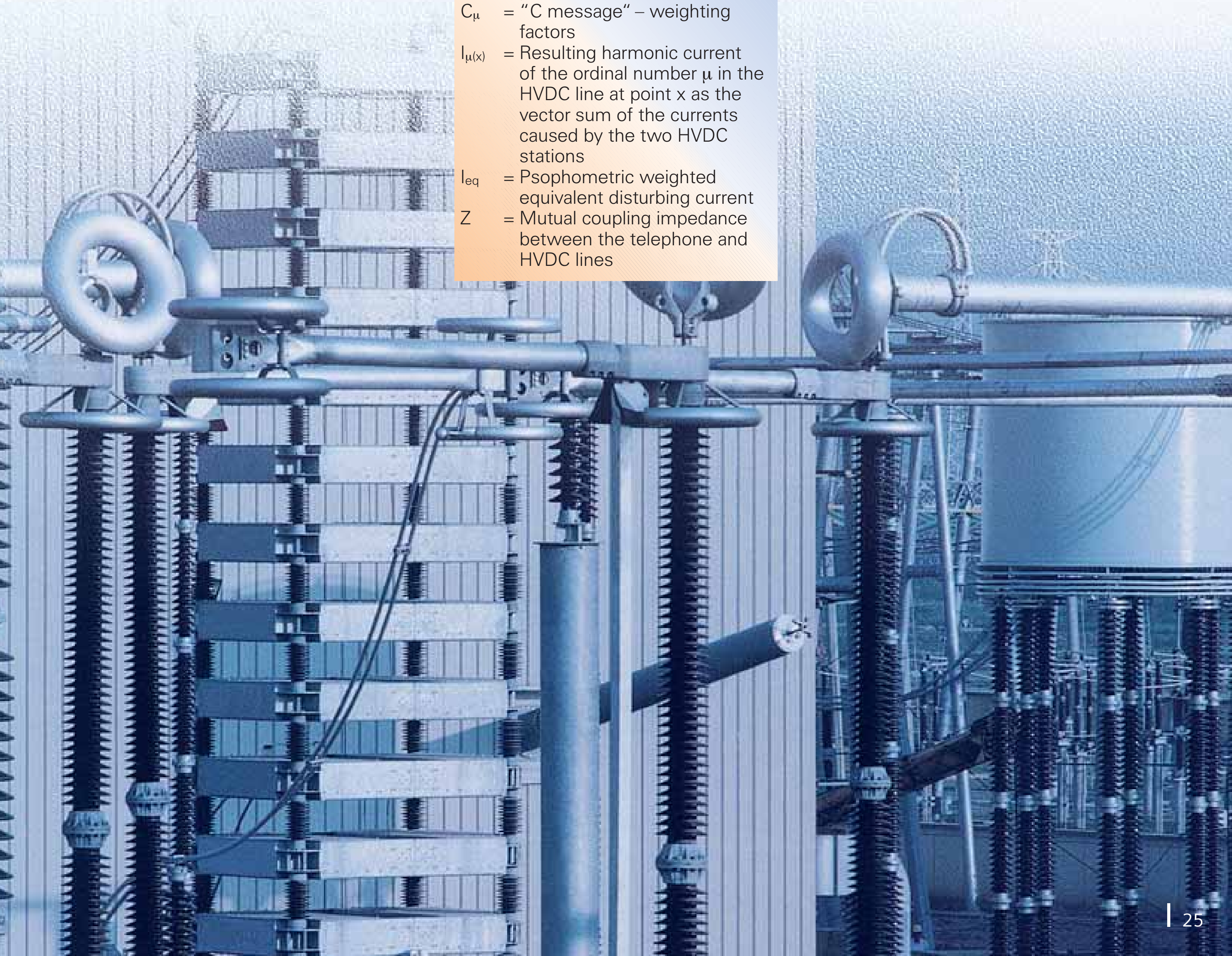
where

$V_{in(x)}$ = Interference voltage on the telephone line at point x (in mV/km)
H_μ = Weighting factors which reflect the frequency dependence of the coupling between telephone and HVDC lines
C_μ = "C message" – weighting factors
$I_{\mu(x)}$ = Resulting harmonic current of the ordinal number μ in the HVDC line at point x as the vector sum of the currents caused by the two HVDC stations
I_{eq} = Psophometric weighted equivalent disturbing current
Z = Mutual coupling impedance between the telephone and HVDC lines

The equivalent disturbing current combines all harmonic currents with the aid of weighting factors to a single interference current. With respect to telephone interference, it is the equivalent to the sum of all harmonic currents. It also encompasses the factors which determine the coupling between the HVDC and telephone lines:

- Operating mode of the HVDC system (bipolar or monopolar with metallic or ground return)
- Specific ground resistance at point x

The intensity of interference currents is strongly dependent on the operating condition of the HVDC. In monopolar operation, telephone interference is significantly stronger than in bipolar operation.



5.4.3 Active Harmonic Filter

Fig. 5.4.3-1: Active DC filter on site (Tian Guang HVDC project)

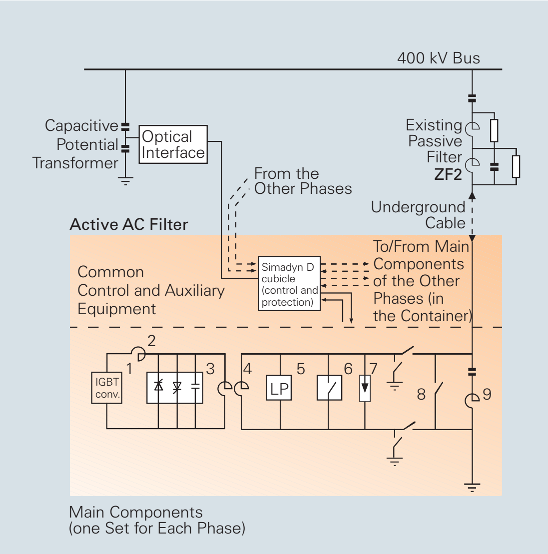


Fig. 5.4.3-2: Single-line diagram of the active AC filter.
All phases have the same topology.

Active filters can be a supplement to passive filters due to their superior performance. They can be installed on the DC side or on the AC side of the converter. The connection to the high-voltage system is achieved by means of a passive filter, forming a so-called hybrid filter. This arrangement limits the voltage level and the transient stresses on the active part, so that comparatively low equipment ratings can be used. Appropriate design allows the exploitation of the positive characteristics of both passive and active filters. Additionally, the passive part can be used as a conventional passive filter if the active part is by-passed for maintenance purposes.

Main Components

No.	Component
1	IGBT converter
2	Reactor for inductivity adapting
3	Thyristor switch for converter overvoltage and overcurrent protection
4	Transformer
5	Low-pass filter
6	Vacuum switch
7	ZnO arrester
8	Isolators and grounding switches
9	LC branch for deviating the 50-Hz current component

The Siemens active filters use voltage-sourced IGBT converters with a high switching frequency to produce an output voltage up to approximately 700 V_{peak}, containing harmonics up to the 50th as required. A powerful high-speed control and protection system processes the currents and/or voltages measured at the network by appropriate sensors and produces the control pulses for the IGBT's.

A transformer matches the voltage and current levels at the converter output and provides the required insulation level. The goal of the scheme is to inject harmonics in the network with the same amplitude and the opposite phase of the harmonics at the measurement point in order to cancel them.

The filter for AC application comprises three single-phase systems controlled by a common digital control system. A major difference is the measurement: instead of measuring the line current, the active filter at Tjele measures and eliminates harmonics at the 400 kV AC busbars of the station. This has the advantage that the harmonic control requires just one measurement point, compared to a current measuring scheme, which would require to measure the current at several points and combining the measured signals. The other advantage is that the active filter works just like a passive filter ideally should do, i.e. eliminating the voltage in the bus, thus representing no change in philosophy.

The active filter is fully assembled in a transportable container and is tested at the factory as a complete system before shipping. Fig. 5.4.3-5 shows the installed active AC filter (in the container) at the Tjele substation.

One harmonic controller is dedicated to each harmonic selected for elimination by the action of the active filter. In these harmonic controllers, the particular harmonic is isolated and expressed by a complex signal in the frequency domain.

This is done through multiplication by sin (hωt) and cos (hωt), where h is the order of the harmonic, ω the network angular frequency and t the time. These two orthogonal signals are produced by a module synchronized by the fundamental component of the filter current. The signal pair obtained after the mentioned multiplication and filtering feeds a complex controller with PI characteristic. The output of the controller is then shifted back to the time domain by multiplication by cos (hωt) and sin (hωt).

The process is essentially linear, so that all harmonic controllers can operate simultaneously and the sum of all harmonic controller outputs gives the waveform required by the active filter. This signal is then given to the IGBT control module, which includes a pulse width modulator besides functions for protection and supervision of the converter.

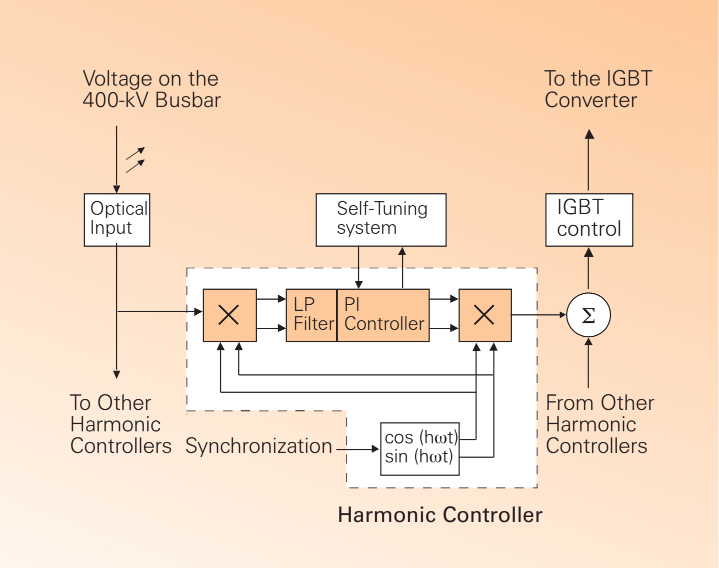
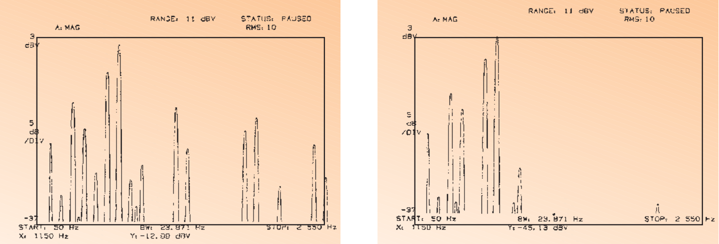


Fig. 5.4.3-3: Principle block diagram of the harmonic control



Harmonic voltages at the 400-kV bus (L1) without and…

…with active filter control (23th, 25th, 35th, 47th and 49th harmonics)

Fig. 5.4.3-4: Plots from measurement: left without, right with active filter control

Fig. 5.4.3-5: Installation of the active AC filter, 400-kV substation Tjele (Denmark)

5.5 Surge Arrester

Siemens surge arresters are designed optimally to the following requirements:

Excellent pollution performance for coastal and desert regions or in areas with extreme industrial air pollution.

High mechanical stability, e.g. for use in seismic zones.

Extremely reliable pressure relief behaviour for use in areas requiring special protection.

What is more, all Siemens surge arresters are sized for decades and the material used provides a contribution towards the protection of the environment.

The main task of an arrester is to protect the equipment from the effects of overvoltages. During normal operation, it should have no negative effect on the power system. Moreover, the arrester must be able to withstand typical surges without incurring any damage. Non-linear resistors with the following properties fulfil these requirements:

- Low resistance during surges so that overvoltages are limited
- High resistance during normal operation in order to avoid negative effects on the power system and
- Sufficient energy absorption capability for stable operation

MO (Metal Oxide) arresters are used in medium-, high-and extra-high-voltage power systems.

Here, the very low protection level and the high energy absorption capability provided during switching surges are especially important. For high voltage levels, the simple construction of MO arresters is always an advantage.

Arresters with Polymer Housings

Fig. 5.5-2 shows two Siemens MO arresters with different types of housing. In addition to what has been usual up to now – the porcelain housing – Siemens offers also the latest generation of high-voltage surge arresters with polymer housing.

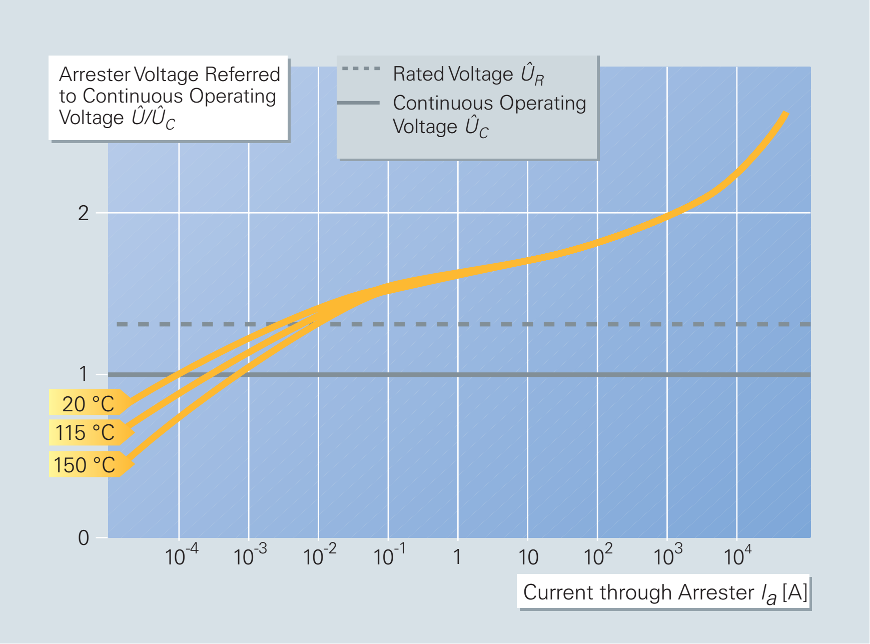


Fig. 5.5-1: Current/voltage characteristics of a non-linear MO arrester

Fig. 5.5-2: Measurement of residual voltage on porcelain-housed (foreground) and polymer-housed (background) arresters

Fig. 5.5-3 shows the sectional view of such an arrester. The housing consists of a fibre-glass-reinforced plastic tube with insulating sheds made of silicon rubber. The advantages of this design which has the same pressure relief device as an arrester with porcelain housing are absolutely safe and reliable pressure relief characteristic, high mechanical strength even after pressure relief and excellent pollution-resistant properties. The very good mechanical features mean that Siemens arresters with polymer housing (type 3EQ/R) can serve as post insulators as well. The pollution-resistant properties are the result of the water-repellent effect (hydrophobicity of the silicon rubber).

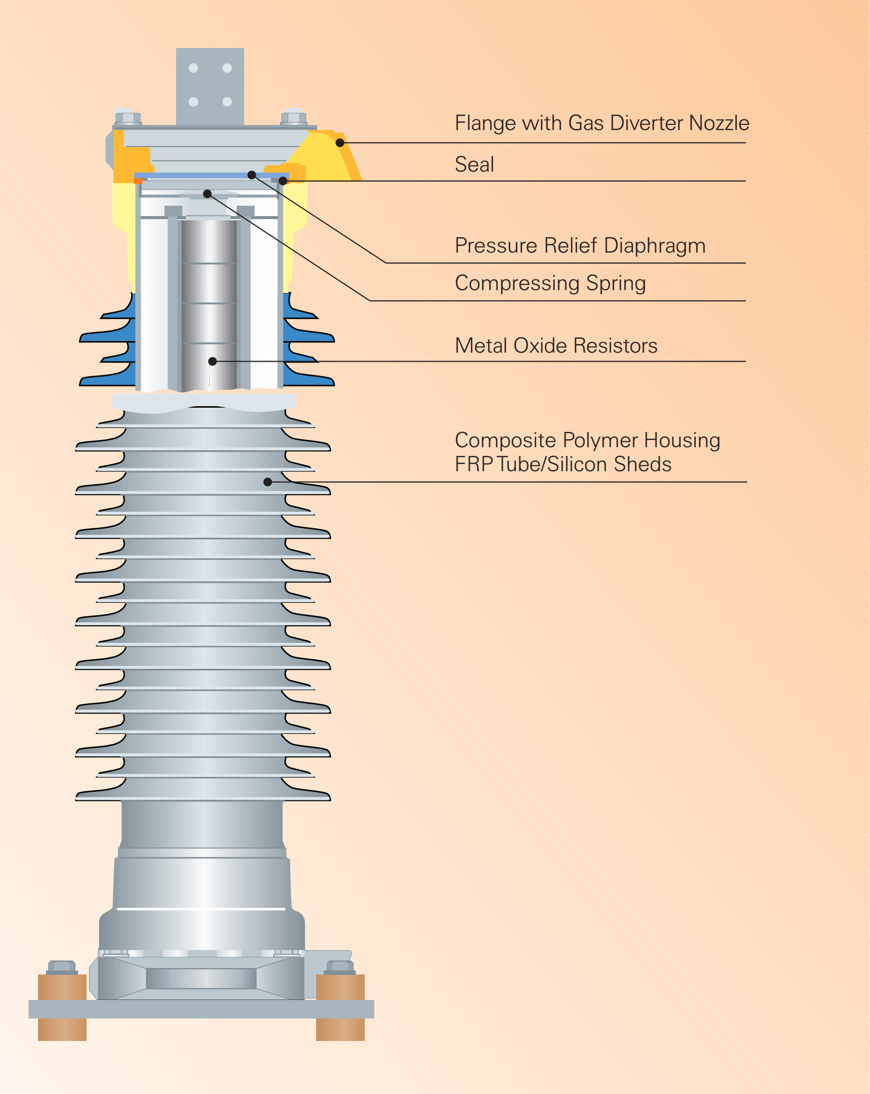
The polymer-housed high-voltage arrester design chosen by Siemens and the high-quality materials used by Siemens provide a whole series of advantages including long life and suitability for outdoor use, high mechanical stability and ease of disposal.

For terminal voltage lower than the permissible maximum operating voltage (MCOV), the arrester is capacitive and carries only few milli-amps. Due to its extreme non-linear characteristics, the arrester behaves at higher voltages as low-ohmic resistor and is able to discharge high current surges. Through parallel combination of two or more matched arrester columns, higher energy absorption capability of the ZnO arrester can be achieved.

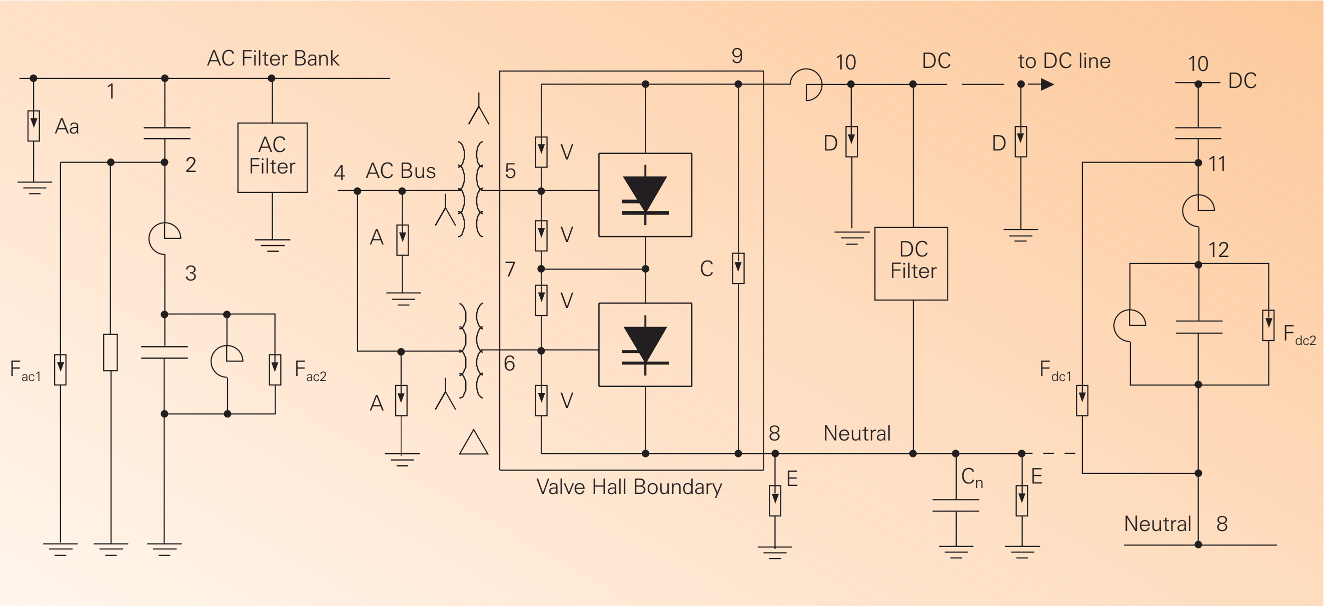
Routine and type tests have been determined in accordance with the international standards:

IEC 60060 High-voltage test techniques
IEC 60071 Insulation coordination
IEC 60099 Surge arresters

Fig. 5.5-3: Cross-section of a polymer-housed arrester



5.5 Surge Arrester



Arrester Type	**Location**	**Main Task**
AC bus arrester ‘A’	The ZnO arrester will be installed close to the converter transformer line side bushing	Limit the overvoltages on the primary and secondary side of the converter transformer
AC filter bus arrester ‘Aa’	The ZnO arrester will be installed at the busbar of the AC filter banks	Protect the AC filters busbar against lightning surges
Valve-arrester ‘V’	3-pulse commutation group	The main events to be considered with respect to arrester discharge currents and energies are: a) Switching surges from the AC system through converter transformer b) Ground fault between valve and HV bushing of converter transformer during rectifier operation
Converter group arrester ‘C’	12-pulse converter group	Protection against overvoltages from the AC and DC side
DC bus arrester ‘D’	At the HV smoothing reactor and at the DC lines	They will protect the smoothing reactor and the converter station (e.g. DC switchyard) against overvoltages coming from the DC side
Neutral DC bus arrester ‘E’	Neutral DC bus	The neutral bus arresters protect the LV terminal of the12-pulse group and the neutral bus equipment
AC filter arrester ‘F_{ac}’	AC filter	The operating voltage for the AC filter arresters consists of low fundamental frequency and harmonic voltages. Overvoltages can occur transiently during faults
DC filter arrester ‘F_{dc}’	DC filter	The operating voltage for the DC filter arresters consists of low DC component and harmonic voltages. Overstresses may occur transiently during DC bus fault to ground

5.6.1 DC Transmission Line

DC transmission lines could be part of overall HVDC transmission contract either within a turnkey package or as separately contracted stand-alone item, later integrated into an HVDC link.

As an example of such a transmission line design, an existing bipolar tower for the 300-kV link between Thailand and Malaysia is shown in Fig.5.6.1-1.

Fig. 5.6.1-1:
DC transmission line
(bipolar tower 300-kV link)

5.6.1.1 Towers

Such DC transmission lines are mechanically designed as it is practice for normal AC transmission lines; the main differences are:

- The conductor configuration
- The electric field requirements
- The insulation design

5.6.1.2 Insulation

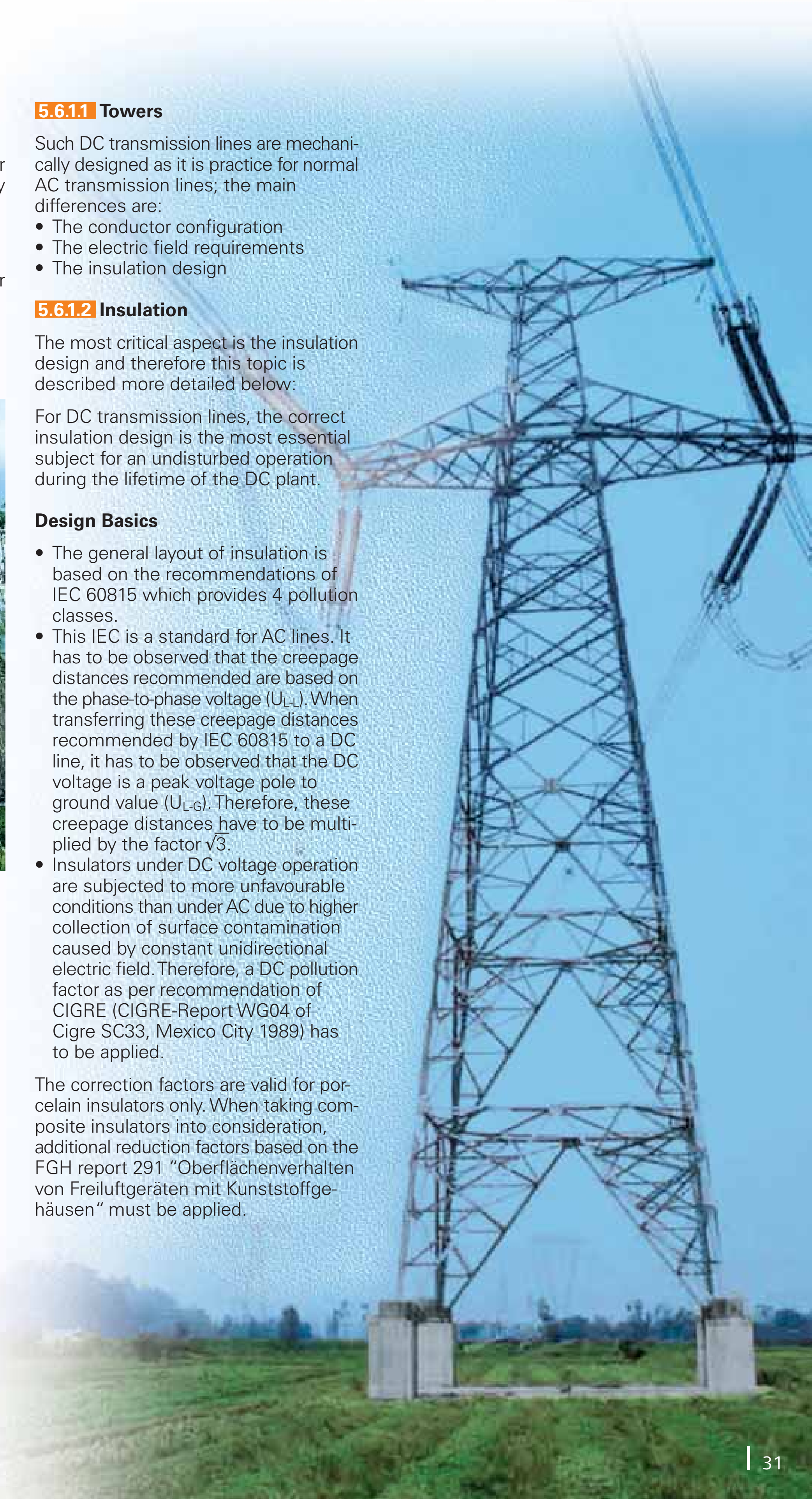
The most critical aspect is the insulation design and therefore this topic is described more detailed below:

For DC transmission lines, the correct insulation design is the most essential subject for an undisturbed operation during the lifetime of the DC plant.

Design Basics

- The general layout of insulation is based on the recommendations of IEC 60815 which provides 4 pollution classes.
- This IEC is a standard for AC lines. It has to be observed that the creepage distances recommended are based on the phase-to-phase voltage (U_{L-L}). When transferring these creepage distances recommended by IEC 60815 to a DC line, it has to be observed that the DC voltage is a peak voltage pole to ground value (U_{L-G}). Therefore, these creepage distances have to be multiplied by the factor $\sqrt{3}$.
- Insulators under DC voltage operation are subjected to more unfavourable conditions than under AC due to higher collection of surface contamination caused by constant unidirectional electric field. Therefore, a DC pollution factor as per recommendation of CIGRE (CIGRE-Report WG04 of Cigre SC33, Mexico City 1989) has to be applied.

The correction factors are valid for porcelain insulators only. When taking composite insulators into consideration, additional reduction factors based on the FGH report 291 “Oberflächenverhalten von Freiluftgeräten mit Kunststoffgehäusen“ must be applied.



5.6.1 DC Transmission Line

Types of Insulators

There are 3 different types of insulators applicable for DC transmission lines:
- Cap and pin type
- Long-rod porcelain type
- Composite long-rod type

In detail:

Cap and Pin Type

Positive Aspects:
- Long-term experience/track record
- Good mechanical strength
- Vandalism-proof
- Flexibility within the insulator string

Negative Aspects:
- Very heavy strings
- Insulator not puncture-proof
- Poor self-cleaning ability
- Loss of strength/reliability due to corrosion of pin in polluted areas caused by high track current density (this is extremely important for DC lines)
- Many intermediate metal parts
- High RIV and corona level
- For DC applications, special shed design and porcelain material necessary
- Very expensive

Long-Rod Porcelain Type

Positive Aspects:
- Long-term experience/track record
- Good mechanical strength
- Puncture-proof
- Good self-cleaning ability
- Less intermediate metal parts
- Due to caps on both insulator ends not subjected to pin corrosion because of low track current density
- Moderate price

Negative Aspects:
- Heavy strings
- String not very flexible
- Under extreme vandalism failure of string possible

Composite Long-Rod Type

Positive Aspects:
- Small number of insulators in one string
- Up to 400 kV per unit possible
- Good mechanical strength, no chipping of sheds possible
- Very light – easy handling during construction and maintenance, logistical advantages in areas with poor access
- Puncture-proof
- Good self-cleaning behaviour – hydrophobicity of surface which offers advantages of less creepage distance up to pollution class II
- Very good RIV and corona behaviour
- Good resistance against vandalism
- Shorter insulator string length
- Very competitive price

Negative Aspects:
- Relatively short track record in DC application (since 1985 first major application in the USA)
- Less tracking resistance against flashover (can be improved by means of corona rings)

Example/Comparison of Insulator Application for a 400 kV Transmission Line

	Cap and Pin	Porcelain Long-Rod	Composite Long-Rod
Insulator string length	5270 mm 31 insulators	5418 mm 4 insulators	4450 mm 1 insulator
Creepage per unit	570 mm	4402 mm	17640 mm
Weight of string	332 kg	200 kg	28 kg
Breaking load	160 kN	160 kN	160 kN

5.6.2.1 General Application for DC Cables

An important application for HVDC are transmission systems crossing the sea. Here, HVDC is the preferred technology to overcome distances > 70 km and transmission capacities from several hundred to more than a thousand MW (for bipolar systems). For the submarine transmission part, a special cable suitable for DC current and voltage is required.

5.6.2.2 Different Cable Types

For HVDC submarine cables there are different types available.

1) Mass-Impregnated Cable
This cable type is used in most of the HVDC applications. It consists of different layers as shown in Fig. 5.6.2.2-1.

The conductor is built of stranding copper layers of segments around a central circular rod. The conductor is covered by oil and resin-impregnated papers. The inner layers are of carbon-loaded papers whereas the outer layer consists of copper-woven fabrics.
The fully impregnated cable is then lead-sheathed to keep the outside environment away from the insulation. The next layer is the anti-corrosion protection which consists of extruded polyethylene. Around the polyethylene layer galvanized steel tapes are applied to prevent the cable from permanent deformation during cable loading. Over the steel tapes a polypropylene string is applied followed by galvanized steel wire armour.
The technology is available for voltages up to 500 kV and a transmission capacity of up to 800 MW in one cable with installation depths of up to 1000 m under sea level and nearly unlimited transmission lengths. The capacity of mass-impregnated cables is limited by the conductor temperature which results in low overload capabilities.

2) Oil-Filled Cable
In comparison to mass-impregnated cables, the conductor is insulated by paper impregnated with a low-viscosity oil and incorporates a longitudinal duct to permit oil flow along the cable. Oil-filled cables are suitable for both AC and DC voltages with DC voltages up to 600 kV DC and great sea depths. Due to the required oil flow along the cable, the transmission line lengths are however limited to <100 km and the risk of oil leakage into the environment is always subject to discussions.

5.6.2.3 Future Developments for HVDC Cables

Most of the research and development activities for new cable types are done with the insulation material. These include:

1) XLPE

To overcome the disadvantages of the above mentioned cable types, extensive R&D was conducted by the cable suppliers. The result is the XLPE cable. XLPE means ‘cross-linked polyethylene‘ and forms the insulation material. The conductor is the segmented copper conductor insulated by extruded XLPE layers. The insulation material is suitable for a conductor temperature of 90°C and a short-circuit temperature of 250°C. Although the main application for XLPE cables is the land installation and the offshore industry, XLPE with extruded insulation material for HVDC systems of lower transmission capacities are under development.

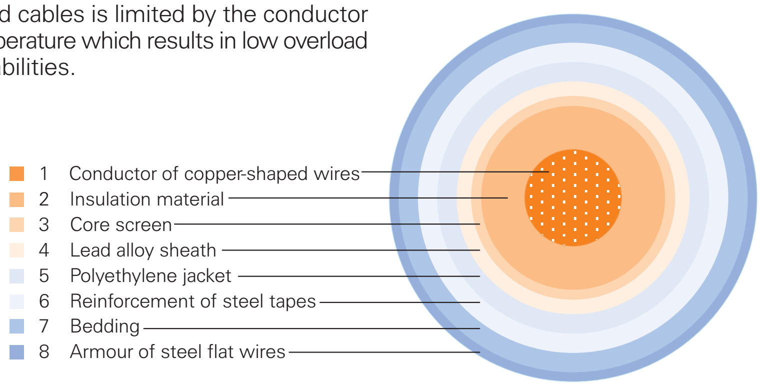


Fig. 5.6.2.2-1: Mass-impregnated cable

2) Lapped Thin Film Insulation

As insulating material a lapped non-impregnated thin PP film is used instead of the impregnated materials. The tests for the cable itself are completed. Now the tests for the accessories such as joints are under process.
This type of cable can sustain up to 60% higher electrical stresses in operation, making it suitable for very long and deep submarine cables.

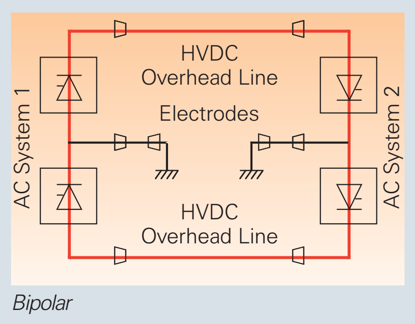
Another area of development are the cable arrangements. For monopolar transmission systems, either the return path was the ground (‘ground return‘) or a second cable. The first solution always provokes environmental concerns whereas the second one has excessive impact on the costs for the overall transmission scheme.
Therefore, a new cable was developed with an integrated return conductor. The cable core is the traditional design for a mass-impregnated cable and the return conductor is wound outside the lead sheath. The conductor forms also part of the balanced armour, together with the flat steel wire layer on the outside of the return conductor insulation.
This cable type was installed between Scotland and Northern Ireland for 250 kV and 250 MW. R&D is ongoing to increase the voltage as well as the capacity of the cable with integrated return conductor.

5.6.3 High Speed DC Switches

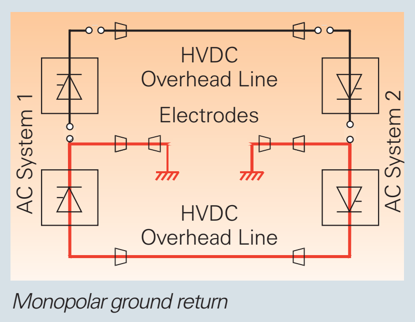
5.6.3.1 General

Like in AC substations, switching devices are also needed in the DC yard of HVDC stations. One group of such devices can be characterized as switches with direct current commutation capabilities, commonly called "high-speed DC switches".

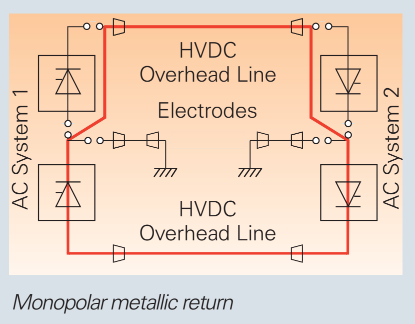
Siemens standard SF_6 AC circuit-breakers of proven design are able to meet the requirements of high-speed DC switches.



Bipolar



Monopolar ground return



Monopolar metallic return

Fig. 5.6.3-1: HVDC system configurations

5.6.3.2 Types and Duties of the High-Speed DC Switches

Type	Duties
HSNBS (High-Speed Neutral Bus Switch)	The HSNBS must commutate some direct current into the ground electrode path in case of faults to ground at the station neutral.
HSGS (High-Speed Ground Switch)	The HSGS is needed to connect the station neutral to the station ground grid if the ground electrode path becomes isolated.
MRTB (Metallic Return Transfer Breaker)	If one pole of a bipolar system has to be blocked, monopolar operation of the second pole is achieved automatically, but with return current through ground (refer to Fig. 5.6.3-1). If the duration of ground return operation is restricted, an alternate mode of monopolar operation is possible if the line of the blocked pole can be used for current return. This mode is called metallic return (refer to Fig. 5.6.3-1). The MRTB is required for the transfer from ground to metallic return without interruption of power flow.
GRTS (Ground Return Transfer Switch)	The GRTS is needed for the retransfer from metallic return to bipolar operation via ground return, also without interruption of power flow.

MRTB at Tian Guang/China DC switchyard

5.6.3.3 Design Considerations

Details regarding the duties of "HSNBS" and "HSGS" are not discussed here but the more severe requirements for "MRTB" and "GRTS" are explained.

Fig. 5.6.3-2 shows the disposition of MRTB and GRTS. R_m and L_m represent resistance and inductance of the transmission line. R_e and L_e comprise resistances and inductances of the ground return path.

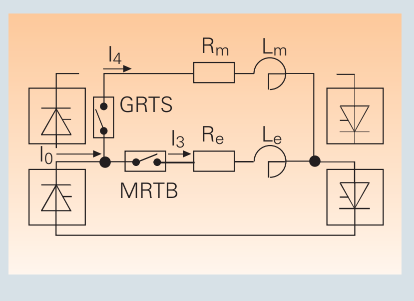


Fig. 5.6.3-2: Equivalent circuit relevant to MRTB and GRTS operation

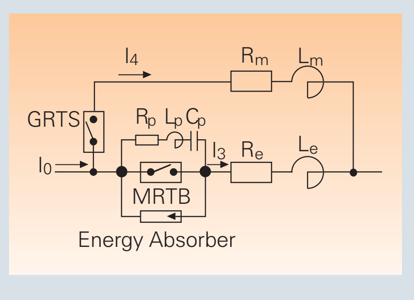


Fig. 5.6.3-3: Details of the MRTB circuit

The ground resistance R_e is normally much lower than the metallic resistance R_m. Therefore, during the transitional steady-state condition with both MRTB and GRTS closed, most of the current is flowing through ground which determines the commutation requirements for MRTB and GRTS. I_3 may reach values of up to 90% of the total current I_0 and I_4 values of up to 25% of I_0.

The following considerations refer to MRTB only. From the above it can be concluded that the commutation duties for transfer from ground to metallic return (MRTB) are much heavier than from metallic to ground return (GRTS).

Fig. 5.6.3-3 shows the basic MRTB circuit. An energy absorber and the L_pC_p resonant circuit (R_p represents the ohmic resistance of that branch only) are connected in parallel to the main switch (MRTB) which is a conventional SF_6-type AC breaker.

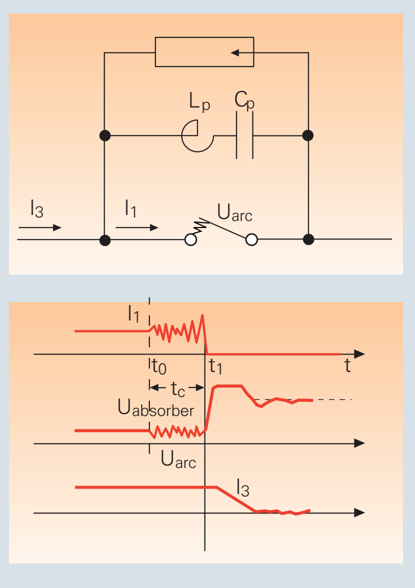


Fig. 5.6.3-4: Principles of MRTB operation

With reference to Fig 5.6.3-4, the principle of commutation is as follows: At t_0, the contacts of the breaker separate, thereby introducing an arc into the circuit. The characteristic of this arc sets up an oscillatory current (frequency determined by L_p C_p) which is superimposed on the current I_1. As R_p is very small, the oscillation is not damped but increases. As soon as the current I_1 passes through zero (refer to t_1 in Fig. 5.6.3-4), the breaker current is interrupted. I_3, however, remains unchanged now charging the capacitor C_p until it reaches a voltage limited by the energy absorber. This voltage acts as a counter voltage to reduce the current I_3 and to increase the current I_4 (refer to Fig. 5.6.3-4 and Fig. 5.6.3-3). When the absorber limiting voltage has been reached, the current I_3 flows into the absorber which dissipates an amount of energy determined by the counter voltage to bring I_3 to zero. When I_3 has dropped to zero, I_4 equals I_0 and the current commutation from ground to metallic return has been completed. It should be noted that the current I_0 of the system (refer to Fig. 5.6.3-2) did not change, i.e. the power transmission was never interrupted.

There are also MRTB principles other than the explained one which are based on complex resonant circuits, externally excited with additional auxiliary power sources. With respect to reliability and availability, the advantage of the above principle with passive resonant circuit which is used by Siemens is quite evident. The nozzle system and specifically the flow of SF_6 gas in the Siemens standard SF_6 AC breakers result in an arc characteristic which ensures reliable operation of the passive resonant circuit. One unit of a standard three-phase AC breaker is used.

Extensive series of laboratory tests have shown the capabilities of Siemens SF_6 breakers for this application. Furthermore, such switches are successfully in operation in various HVDC schemes.

5.6.4 Earth Electrode

5.6.4.1 Function of the Earth Electrode in the HVDC System

Earth electrodes are an essential component of the monopolar HVDC transmission system, since they carry the operating current on a continuous basis. They contribute decisively to the profitability of low-power HVDC systems, since the costs for a second conductor (with half the nominal voltage) are significantly higher, even for transmission over short distances, than the costs for the earth electrodes.

Earth electrodes are also found in all bipolar HVDC systems and in HVDC multi-point systems. As in any high-voltage system, the power circuit of the HVDC system requires a reference point for the definition of the system voltage as the basis for the insulation coordination and overvoltage protection. In a bipolar HVDC system, it would conceivably be possible to connect the station neutral point to the ground mat of the HVDC station to which the line-side star points of the converter transformers are also connected. But since the direct currents in the two poles of the HVDC are never absolutely equal, in spite of current balancing control, a differential current flows continuously from the station neutral point to ground. It is common practice to locate the grounding of the station neutral point at some distance (10 to 50 kilometres) from the HVDC station by means of special earth electrodes.

5.6.4.2 Design of Earth Electrodes

Earth electrodes for HVDC systems may be land, coastal or submarine electrodes. In monopolar HVDC systems, which exist almost exclusively in the form of submarine cable transmission systems, there are fundamental differences between the design of anode and cathode electrodes.

5.6.4.2.1 The Horizontal Land Electrode

If a sufficiently large area of flat land with relatively homogeneous ground characteristics is available, the horizontal ground electrode is the most economical form of a land electrode.

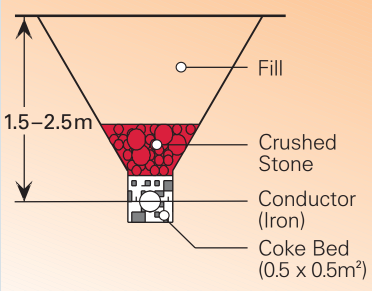
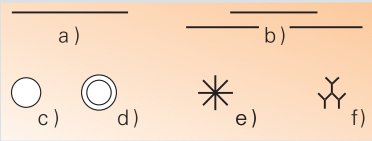


Fig. 5.6.4-1: Cross section through a horizontal land electrode

As shown in figure 5.6.4-1, the electrode conductor itself, which is generally made of iron, is laid horizontally at a depth of approximately 2 m. It is embedded in coke which fills a trench having a cross section of approximately 0.5 x 0.5 m².

The advantage of this design becomes apparent in anodic operation. The passage of the current from the electrode conductor into the coke bed is carried primarily by electrons, and is thus not associated with loss of the material.

Several typical patterns of horizontal land electrodes are illustrated in figure 5.6.4-2



a) Line Electrode
b) Multi-Line Electrode
c) Ring-Shaped Electrode
d) Ring-Shaped Electrode with second ring
e) Star-Shaped Electrode
f) Forked Star Electrode

Fig. 5.6.4-2: Plan view of a typical design of horizontal land electrodes

5.6.4.2.2 Vertical Land Electrode

If the ground strata near the surface have a high specific resistance, but underneath, there is a conductive and sufficiently thick stratum at a depth of several tens of meters, the vertical deep electrode is one possible solution.

Figure 5.6.4-3 shows, as an example, one of the four deep electrodes at Apollo, the southern station of the Cahora Bassa HVDC system.

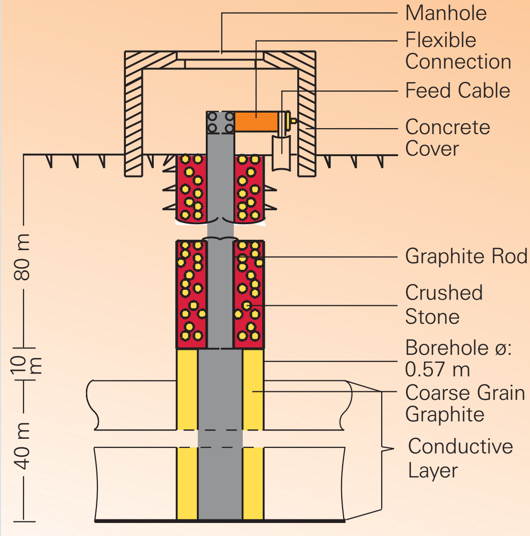


Fig. 5.6.4-3: Vertical electrode at Apollo, the Southern Cahora Bassa HVDC station

5.6.4.2.3 Cathodic Submarine Electrodes

The design and construction of the cathodic submarine electrodes of a monopolar HVDC system with submarine power transmission cable do not present any particular problems. Since there is no material corrosion, a copper cable laid on the bottom should theoretically suffice. The length of the cable must be designed so that the current density on its surface causes an electrical field of < 3 V/m in the surrounding water, which is also safe for swimmers and divers.

5.6.4.2.4 Anodic Submarine Electrodes

Figure 5.6.4-4 shows an example of a linear submarine electrode for anodic operation. The prefabricated electrode modules are lowered to the ocean floor and then connected to the feed cable. When the submarine electrodes are divided into sections which are connected to the HVDC station by means of separate feed cables, the electrode can be monitored from the land.

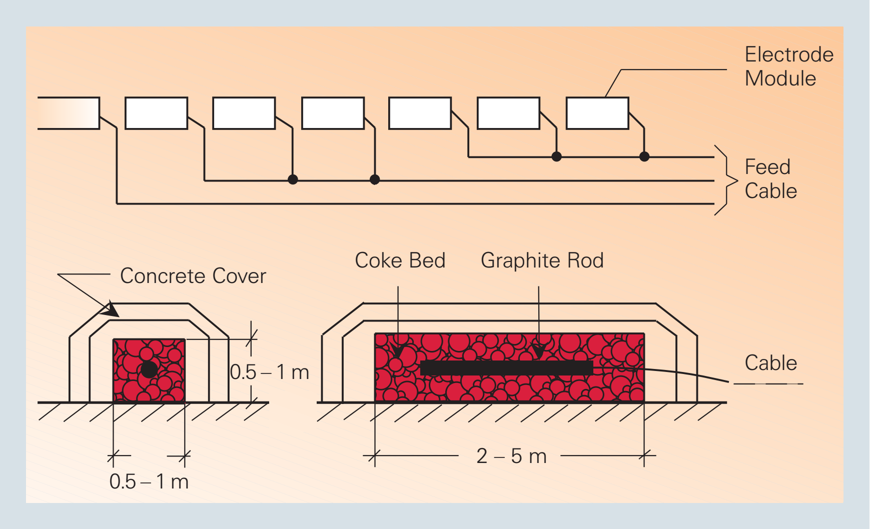


Fig. 5.6.4.-4: Linear submarine electrode (anodic operation)

5.6.4.2.5 Anodic Coastal Electrode

The conventional design of a coastal electrode is similar to that of a vertical land electrode. Graphite rods surrounded by a coke bed are installed in boreholes which are sunk along the coastline.

The advantage of the coastal electrodes is easy accessibility for inspection, maintenance and regeneration, if necessary.

A coastal electrode can also be configured in the form of a horizontal land electrode if the ground has the necessary conductivity or if the necessary conductivity can be achieved by irrigating the trench with salt water. In either case, it is assumed that even with a coastal electrode, the current flow to the opposite electrode takes place almost exclusively through the water.

5.7 Control & Protection

5.7.1 General

The WIN-TDC Control and Protection System plays an important role in the successful implementation of HVDC transmission systems. High reliability is guaranteed with a redundant and fault tolerant design. Flexibility (through choice of optional control centres) and high dynamic performance were the prerequisites for the development of our control and protection system. Knowledge gained from over 30 years of operational experience and parallel use of similar technology in related fields has been built into the sophisticated technology we can offer today.

Main objectives for the implementation of the HVDC control system are reliable energy transmission which operates highly efficient and flexible energy flow that responds to sudden changes in demand thus contributing to network stability.

All WIN-TDC components from the Human Machine Interface (HMI) workstations, the control and protection systems down to the state of the art measuring equipment for DC current and voltage quantities have been upgraded to take advantage of the latest software and hardware developments. These control and protection systems are based on standard products with a product life cycle for the next 25 years.

The control is divided into the following hierarchical levels:

- Operator control level (WIN CC)
- Control and protection level (Simatic TDC)
- Field level (I/Os, time tagging, interlocking)

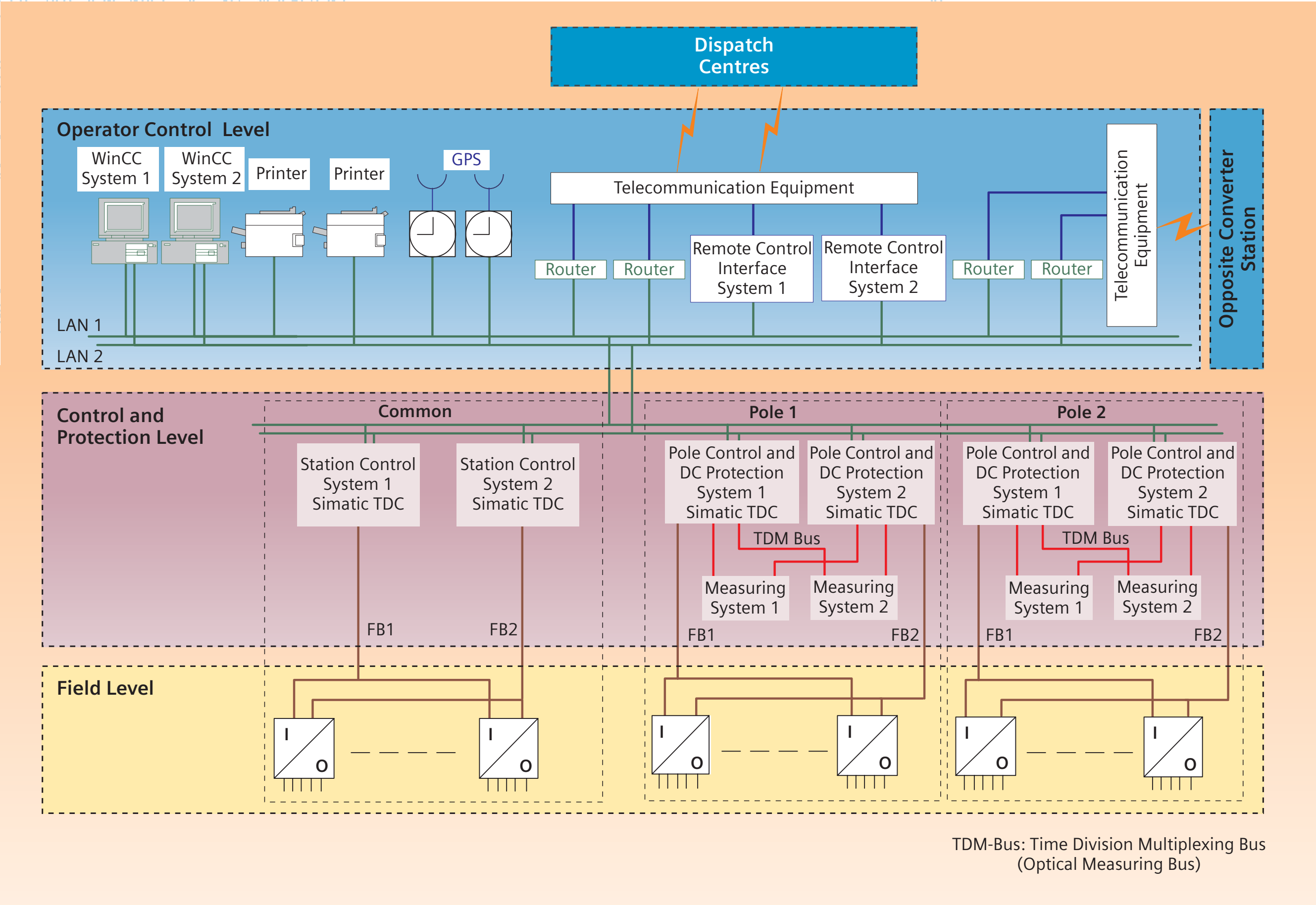


Fig. 5.7.1-1: HVDC control hierarchy, one station (bipolar HVDC transmission scheme)

In the following section, functions, tasks and components are described to provide an overview.

5.7.1.1 High Availability

The main design criteria for Siemens HVDC systems is to achieve maximum energy availability. This applies to the design of the control and protection systems as well. A single fault of any piece of equipment in the control and protection systems may not lead to a loss of power. Therefore, the primary control and protection components are configured as redundant systems.

5.7.1.2 Self-Testing Features

All control and protection systems are equipped with self-diagnostic features that allow the operator to quickly identify and replace the defective part to recover redundancy as soon as possible.

5.7.1.3 Low Maintenance

With today's digital systems there is no requirement for routine maintenance. However, should it be necessary to replace single modules, the design is such that there is no operational impact on the HVDC system. This is achieved by designing all primary components as redundant systems, where one system can be switched off without impact on the other system.

5.7.1.4 Best Support – Remote Access

As an optional feature, the control system can be accessed remotely via point-to-point telephone connection or via Internet. This allows remote plant monitoring and fault detection including diagnostics. To ensure the data security, a VPN (Virtual Private Network) encrypted connection is used. Furthermore, a password protected access ensures that only authorized personnel have access.

With the use of a standard web browser, main diagnosis data can be monitored. Expert access to the control components is also possible. This remote access feature provides flexible support for the commissioning and maintenance personnel by our design engineers.

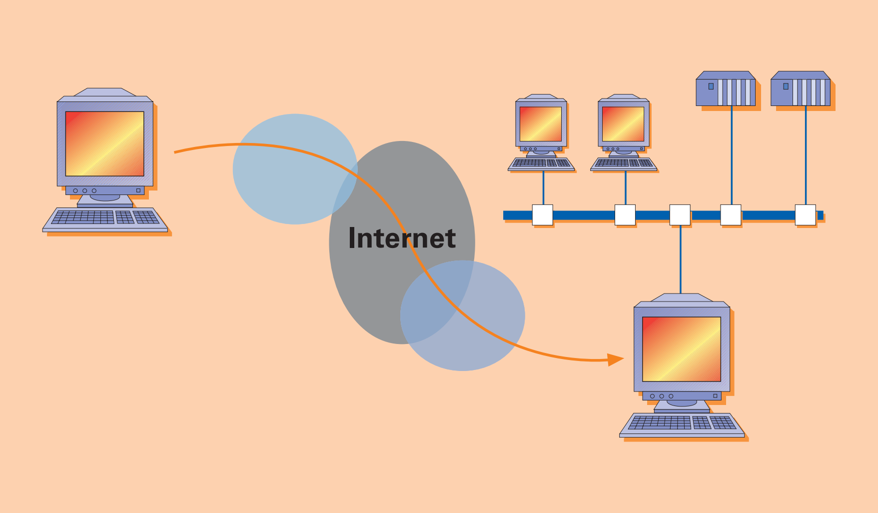


Fig. 5.7.1-2: Remote access connection

5.7.1.5 Modular Design

The control and protection systems use multiprocessor hardware. This means that the computing capacity can be scaled according to the requirements.

Therefore, the most economic solution can be found at the start. Additional computing capacity can be added at any time later, if required.

5.7.1.6 Communication Interfaces

The control and protection systems as well as the operator control system communicate via Ethernet or Profibus. For remote control interfacing, a number of standard protocols are available. Custom protocols can be implemented as an option.

5.7.2 Control Components

5.7.2.1 Operator Control System

The tasks of a modern operation and monitoring system within the HVDC control system include the following:

- Status information of the system
- Operator guidance to prevent maloperation and explain conditions
- Monitoring of the entire installation and auxiliary equipment
- Graphic display providing structural overview of the entire system
- Troubleshooting support with clear messages to quickly resume operation
- Display and sorting of time tagged events (time is synchronised via GPS clock)
- Display and archiving of messages
- Automatic generation of process reports

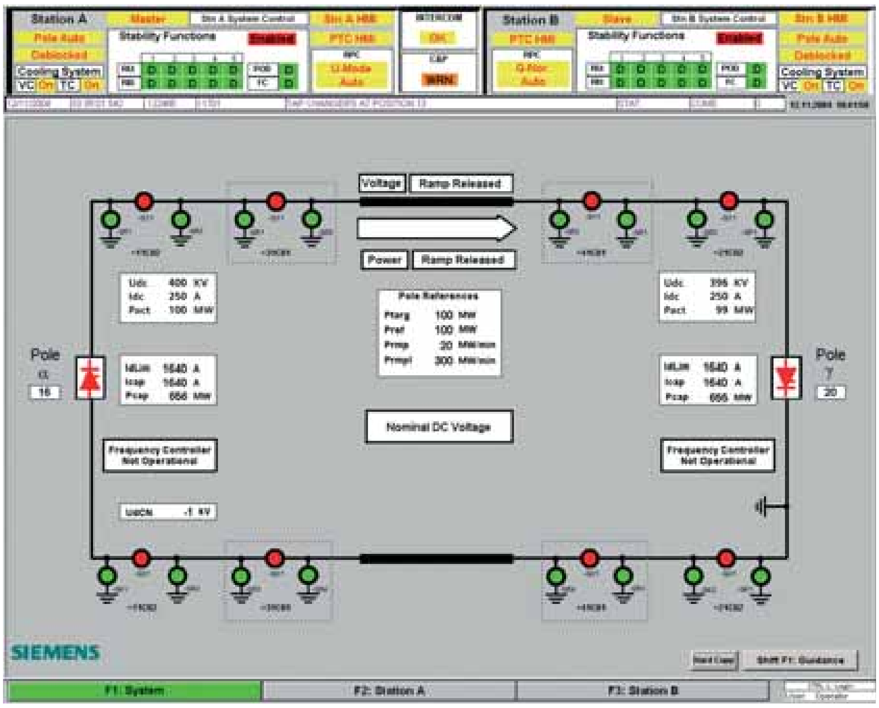
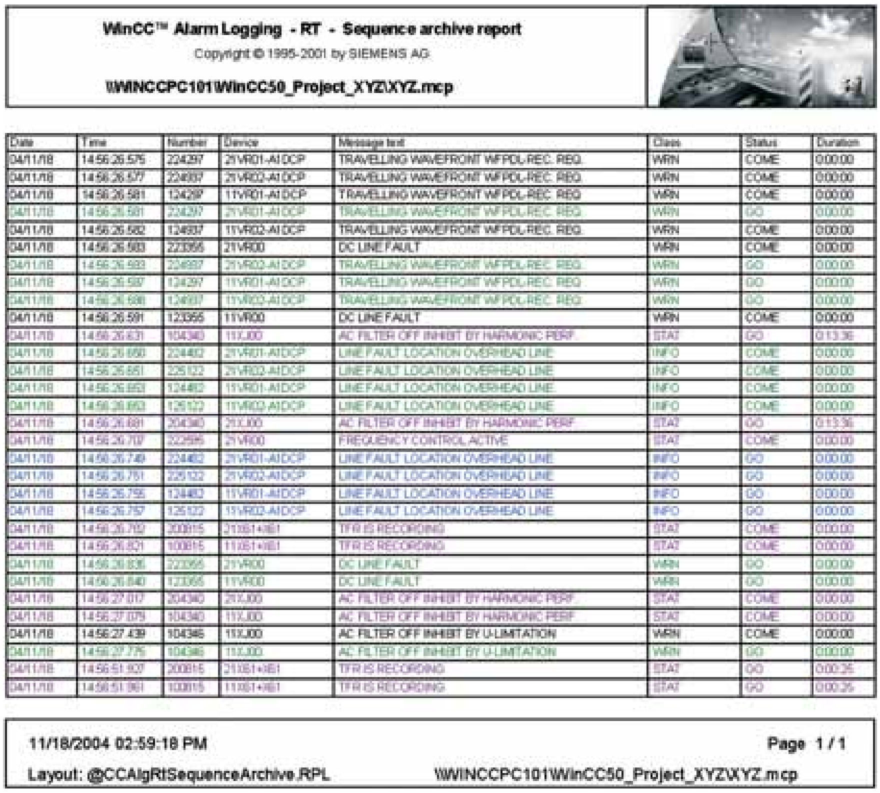


Fig. 5.7.1-3: Operator workstation, typical screen layout for a monopolar HVDC system overview



WinCC™ Alarm Logging - RT - Sequence archive report

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\\WINCCPC101\WinCC50_Project_XYZ\XYZ.mcp

Date	Time	Number	Device	Message text	Class	Status	Duration
04/11/18	14:56:26.575	224297	21VR01-A1DCP	TRAVELLING WAVEFRONT WFPDL-REC. REQ.	WRN	COME	0:00:00
04/11/18	14:56:26.577	224897	21VR02-A1DCP	TRAVELLING WAVEFRONT WFPDL-REC. REQ.	WRN	COME	0:00:00
04/11/18	14:56:26.581	124297	11VR01-A1DCP	TRAVELLING WAVEFRONT WFPDL-REC. REQ.	WRN	COME	0:00:00
04/11/18	14:56:26.581	224297	21VR01-A1DCP	TRAVELLING WAVEFRONT WFPDL-REC. REQ.	WRN	GO	0:00:00
04/11/18	14:56:26.582	124897	11VR02-A1DCP	TRAVELLING WAVEFRONT WFPDL-REC. REQ.	WRN	COME	0:00:00
04/11/18	14:56:26.583	223366	21VR00	DC LINE FAULT	WRN	COME	0:00:00
04/11/18	14:56:26.583	224897	21VR02-A1DCP	TRAVELLING WAVEFRONT WFPDL-REC. REQ.	WRN	GO	0:00:00
04/11/18	14:56:26.587	124297	11VR01-A1DCP	TRAVELLING WAVEFRONT WFPDL-REC. REQ.	WRN	GO	0:00:00
04/11/18	14:56:26.588	124897	11VR02-A1DCP	TRAVELLING WAVEFRONT WFPDL-REC. REQ.	WRN	GO	0:00:00
04/11/18	14:56:26.591	123366	11VR00	DC LINE FAULT	WRN	COME	0:00:00
04/11/18	14:56:26.631	104340	11XJ00	AC FILTER OFF INHIBIT BY HARMONIC PERF.	STAT	GO	0:13:36
04/11/18	14:56:26.650	224482	21VR01-A1DCP	LINE FAULT LOCATION OVERHEAD LINE	INFO	COME	0:00:00
04/11/18	14:56:26.651	225122	21VR02-A1DCP	LINE FAULT LOCATION OVERHEAD LINE	INFO	COME	0:00:00
04/11/18	14:56:26.653	124482	11VR01-A1DCP	LINE FAULT LOCATION OVERHEAD LINE	INFO	COME	0:00:00
04/11/18	14:56:26.653	125122	11VR02-A1DCP	LINE FAULT LOCATION OVERHEAD LINE	INFO	COME	0:00:00
04/11/18	14:56:26.681	204340	21XJ00	AC FILTER OFF INHIBIT BY HARMONIC PERF.	STAT	GO	0:13:36
04/11/18	14:56:26.707	222595	21VR00	FREQUENCY CONTROL ACTIVE	STAT	COME	0:00:00
04/11/18	14:56:26.749	224482	21VR01-A1DCP	LINE FAULT LOCATION OVERHEAD LINE	INFO	GO	0:00:00
04/11/18	14:56:26.751	225122	21VR02-A1DCP	LINE FAULT LOCATION OVERHEAD LINE	INFO	GO	0:00:00
04/11/18	14:56:26.756	124482	11VR01-A1DCP	LINE FAULT LOCATION OVERHEAD LINE	INFO	GO	0:00:00
04/11/18	14:56:26.757	125122	11VR02-A1DCP	LINE FAULT LOCATION OVERHEAD LINE	INFO	GO	0:00:00
04/11/18	14:56:26.792	200815	21X61+X61	TFR IS RECORDING	STAT	COME	0:00:00
04/11/18	14:56:26.801	100815	11X61+X61	TFR IS RECORDING	STAT	COME	0:00:00
04/11/18	14:56:26.836	223366	21VR00	DC LINE FAULT	WRN	GO	0:00:00
04/11/18	14:56:26.840	123366	11VR00	DC LINE FAULT	WRN	GO	0:00:00
04/11/18	14:56:27.017	204340	21XJ00	AC FILTER OFF INHIBIT BY HARMONIC PERF.	STAT	COME	0:00:00
04/11/18	14:56:27.079	104340	11XJ00	AC FILTER OFF INHIBIT BY HARMONIC PERF.	STAT	COME	0:00:00
04/11/18	14:56:27.439	104346	11XJ00	AC FILTER OFF INHIBIT BY U-LIMITATION	WRN	COME	0:00:00
04/11/18	14:56:27.776	104346	11XJ00	AC FILTER OFF INHIBIT BY U-LIMITATION	WRN	GO	0:00:00
04/11/18	14:56:51.927	200815	21X61+X61	TFR IS RECORDING	STAT	GO	0:00:25
04/11/18	14:56:51.961	100815	11X61+X61	TFR IS RECORDING	STAT	GO	0:00:25

11/18/2004 02:59:18 PM **Page 1 / 1**

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Fig. 5.7.1-4: Sequence of events recording (SER), report layout for SER information

- Analysis of operating mode based on user-defined and archived data (trend system)
- Generation of process data reports

Fig. 5.7.1-5: Trend system, example for trend display

5.7.2.2 Control and Protection System Level

The primary tasks in this level are:

- Measuring
- Control of Power Transmission
- Protection

Measuring

DC values are measured by means of the hybrid optical DC measuring system. This system measures the voltage drop over a shunt or a voltage divider, converts this voltage into a telegram and transfers it to the measurement cubicle via fibre optics.

The scheme is designed to be completely redundant, therefore loss of a signal does not lead to an impact on power transmission. This measuring principle contributes to an increased availability of the control and protection scheme.

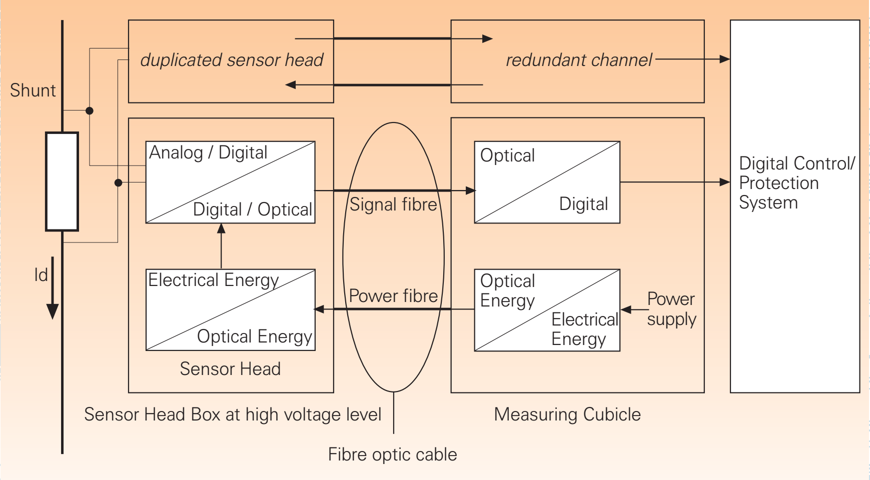


Fig. 5.7.1-6: Principle of the hybrid optical measuring scheme

The advantages of such a scheme are:

- Reduced weight (100 kg)
- Linear response (passive system)
- Improved EMC (due to fibre optics)
- Integrated harmonic measurement (Rogowsky coil) for use in active filters or harmonic monitoring schemes.

5.7 Control & Protection

Control of Power Transmission

The pole control system is responsible for firing the thyristor valves so that the requested power is transmitted. The pole controls on each side of the transmission link therefore have to fulfill different tasks. The pole control system on the rectifier side controls the current so that the requested power is achieved. The pole control system on the inverter side controls the DC voltage so that rated DC voltage is achieved.

The pole control is implemented redundantly. A failure in one system thus has no impact on power transmission.

This system can be repaired while the other system remains in operation. In bipolar schemes a redundant pole control system is assigned to each pole. Failures in one pole will not have any impact on the remaining pole.

Protection

The DC protection system has the task of protecting equipment and personnel. The protection systems can be divided into two areas, which are subsequently divided into different protection zones.

The HVDC-related protection functions are referred to as DC protection. These include converter protection, DC busbar protection, DC filter protection, electrode line protection and DC line protection.

The AC protection scheme consists mainly of the AC busbar, the AC line and the AC grid transformer protection as well as the AC filter protection and converter transformer protection.

The task of the protective equipment is to prevent damage of individual components caused by faults or overstresses.

Each protection zone is covered by at least two independent protective units – the primary protective unit and the secondary (or back-up) protective unit.

Comprehensive system monitoring and measurement plausibility functions are implemented in the protection systems. This serves to prevent false trips due to singular equipment failure.

The protection functions of the various protective relays are executed reliably for all operating conditions. The selected protective systems ensure that all possible faults are detected, annunciated and cleared selectively.

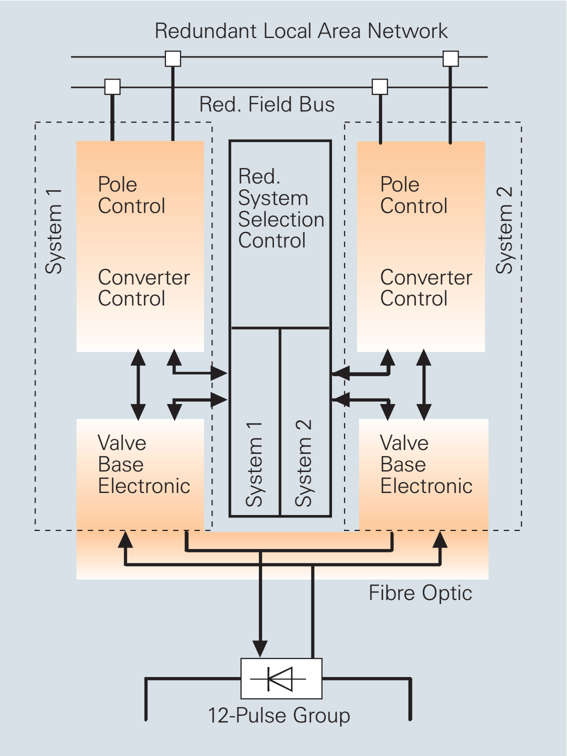


Fig. 5.7.1-7: Redundant pole control system structure (for one 12-pulse group)

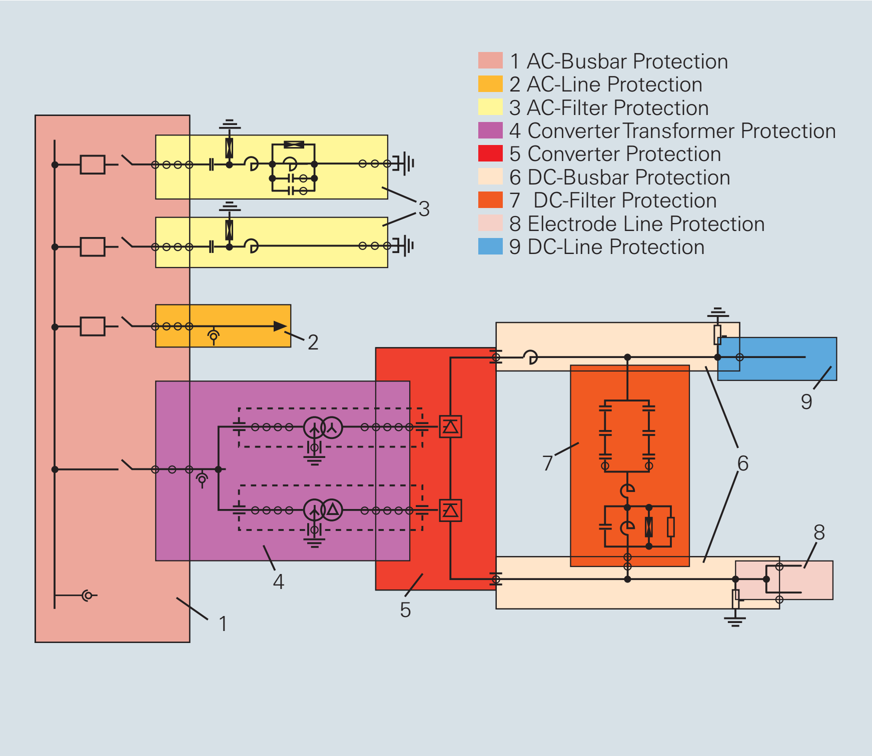


Fig. 5.7.1-8: Protection zones, one pole/one station

All protective equipment in the HVDC converter station is implemented either with digital multi-microprocessor systems or with digital Siemens standard protective relays. "The DC protection is designed to be fully redundant. Additionally both protection systems incorporate main and back-up protection functions using different principles. The AC protection consists of a main and back-up system using different principles. Each protective system is assigned its own measuring devices as well as power supplies."

5.7.3 Control Aspects

5.7.3.1 Redundancy

All control and protection systems that contribute to the energy availability are configured redundantly. This covers any single faults in the control and protection equipment without loss of power.

5.7.3.2 Operator Training

For Siemens HVDC application, an operator training simulator is optionally available. The simulator allows the operator to train with the same hardware and software as in the real process. This simulator consists of the original operator workstation and a simulation PC. The simulation PC runs the HVDC process and feeds the relevant data to the workstation.

5.7.4 Testing and Quality Assurance

The design process has a number of defined review steps. These allow verification of the control and protection system functionality and performance before delivery to site (see figure 5.7.1-10).

Already along with the tender, the use of accurate simulation tools allows to answer specific performance issues that are vital to the customer's grid.

5.7.4.1 Offline Simulation EMTDC

Siemens uses a simulation model that includes all details of control and protection functionality in detail. Thus forecast of real system behaviour is reliable. Therefore it is possible to optimize the application to find the best economic solution while providing the optimum performance.

Fig. 5.7.1-9: Real-time simulator

5.7.4.2 Dynamic Performance Test

The offline simulation with EMTDC is already an extremely accurate forecast of the real system behaviour. To verify the findings and optimize the controller settings, the control and protection systems are additionally tested during the dynamic performance test with a real-time simulator. During that phase, the customer may witness these performance tests of the final control and protection software.

5.7.4.3 Functional Performance Test

In the functional performance test, the dedicated control and protection hardware is installed and tested with a real-time simulator. The purpose of the FPT is to test the proper signal exchange between the various control components as well as the verification of the specified control sequences. This allows optimized commissioning time. Furthermore, customer personnel can participate in this test for operator training and become familiar with the control system.

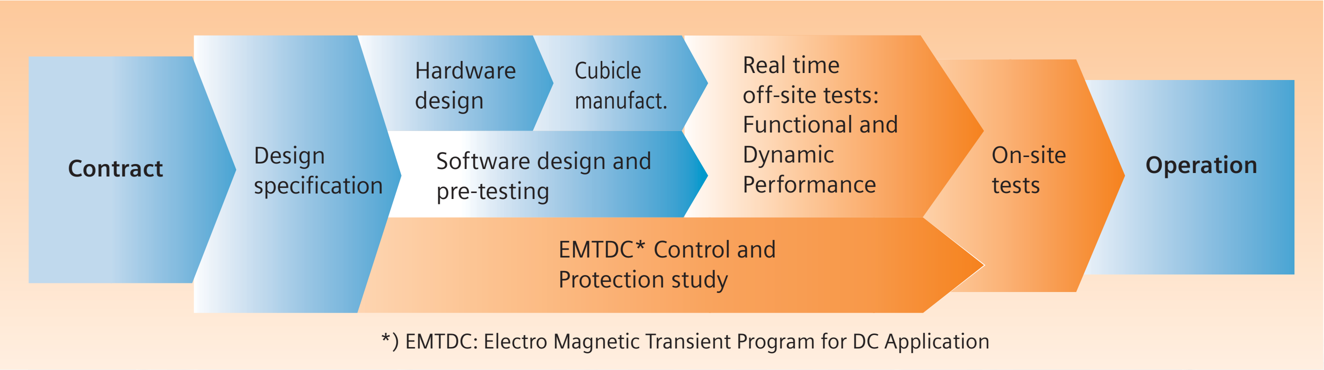
5.7.4.4 On-Site Tests

On-site tests are basically divided into test steps regarding the related station (station A, station B) and into the test steps related to the whole HVDC system.

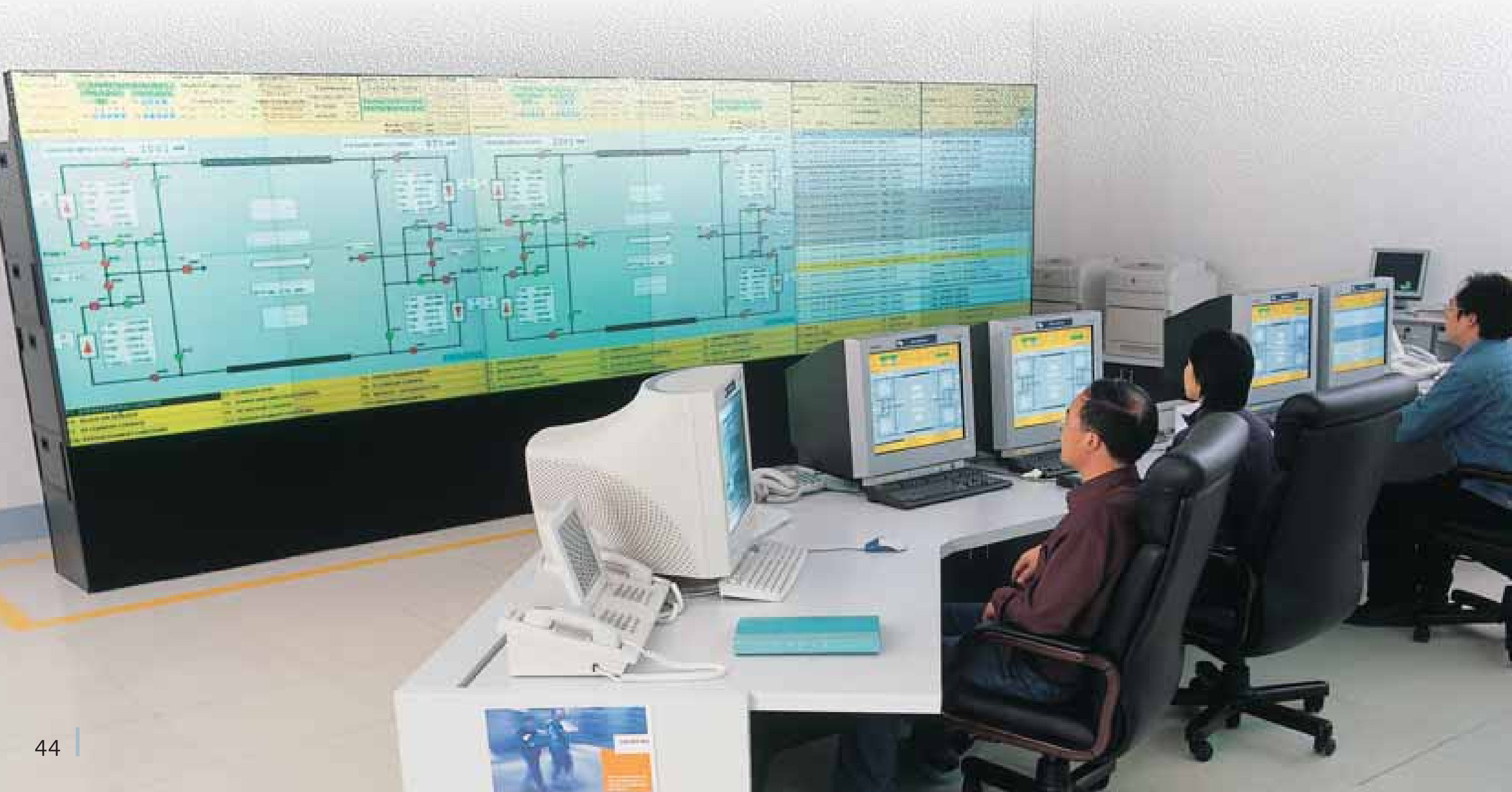
Fig. 5.7.1-11: Example of a functional performance test setup

At the precommissioning stage, the base work for commissioning the control system and protection system is required. The main task is preparation and individual testing of any single system. This is required to assure the systems are free of transportation damage. The next station-related tests are the subsystem tests. Subsystems consist of equipment items which are grouped according to common functions like AC filter banks or thyristor valve systems. The main task is testing the proper function of interconnected systems before switching on high voltage. Following this, station tests with high voltage but no energy transfer will take place. Finally, system and acceptance tests with several operating points of energy transfer will be used for fine tuning and verification of system performance.

Fig. 5.7.1-10: The main steps for the HVDC control and protection versus the time starting from the contract award up to commercial operation



*) EMTDC: Electro Magnetic Transient Program for DC Application



System Studies, **Digital** Models, **Design** Specifications 6

6.1 System Studies

During the planning stage of a HVDC project, preliminary studies are carried out in order to establish the basic design of the whole HVDC transmission project. This includes the co-ordination of all relevant technical parts of the transmission system like HVDC converters, AC and DC overhead lines as well as the submarine cable, if applicable.

All specified requirements will be taken into account and are the basis for the preliminary design of the HVDC transmission link. In addition, special attention is paid to improving the stability of both connected AC systems. Several additional control functions like power modulation, frequency control and AC voltage limiter can be included in order to provide excellent dynamic behaviour and to assist the AC systems if the studies show it necessary. Sub-synchronous oscillation will be avoided by special control functions, if required. All the AC system conditions and the environmental conditions as given in the relevant documents will be considered in the design calculations.

The final design of the HVDC transmission system, including the operation characteristics, will be defined during the detailed system studies. All necessary studies are carried out to confirm the appropriate performance requirements and ratings of all the equipment.

Due consideration is given to the interaction with the AC systems on both sides, the generation of reactive power, system frequency variations, overvoltages, short circuit levels and system inertia during all system configurations.

Typically the following studies are carried out:

a) Main Circuit Parameters
b) Power Circuit Arrangements
c) Thermal Rating of Key Equipment
d) Reactive Power Management
e) Temporary Overvoltages and Ferro-Resonance Overvoltages
f) Overvoltage Protection and Insulation Coordination
g) Transient Current Requirements
h) AC Filter Performance and Rating
i) DC Filter Performance and Rating
j) AC Breaker and DC High-Speed Switch Requirements
k) Electromagnetic Interference
l) Reliability and Availability calculations
m) Loss Calculation
n) Subsynchronous Resonance
o) Load Flow, Stability and Interaction between different HVDC Systems
p) Audible Noise

6.2 Digital Models

Digital models of HVDC system can be developed according to the specified requirements. Typically a digital model of dc system is needed for a specific load flow and stability simulation program, while another digital model is required for simulation in a typical electromagnetic transients program such as EMTDC. The functionality and settings of HVDC control and protection system will be represented in a proper manner in such models, which allow suitable simulation of steady state and transient behavior of HVDC system in the corresponding digital programs. Digital models consistent with the actual dc control and protection system are beneficial both for the operation of the HVDC scheme and for the network studies including DC link. Typically such models can be developed on request in the detailed project design stage when all major design works of control and protection functions are completed.

6.3 Control and Protection Design Specifications

Design Specifications are written for the control, protection and communication hardware and software. The control panels are then designed, manufactured inspected and tested in accordance to the design specification. The software for the control and protection is also written in accordance to the design specification. It is tested using real time simulators in the dynamic performance test and functional performance test.

Specifications for the topics below are typically written:

a) General Control and Protection
b) Interface Systems
c) Station Control
d) Diagnosis Systems
e) Pole Control
f) HVDC Protection
g) AC Protection
h) Metering and Measuring
i) Operator Control
j) Communication

7 Project Management

7.1 Project Management in HVDC Projects

The success and functional completion of large projects depends on the structuring of the project team in accordance with the related work and manpower coordination. Periodical updates and adaptation of design guarantee the execution of the project with constant high quality within the target time frame. Throughout all production, working process and on-site activities, health, safety and environmental protection (HSE) measures as well as application of commonly agreed quality standards such as DIN EN ISO 9001 are of prime importance to Siemens.

7.1.1 Division Responsibilities

The overall project is divided and organised according to design activities and technical component groups. These features make it possible to define clear function packages which are to a great extent homogeneous within themselves and can be processed with minimised interfaces.

7.1.2 Transparency

A clear process structure plan (PSP) standardised for HVDC projects makes the project contents and sequences transparent in their commercial and technical aspects. Associations and interactions are clarified according to procedure of work.

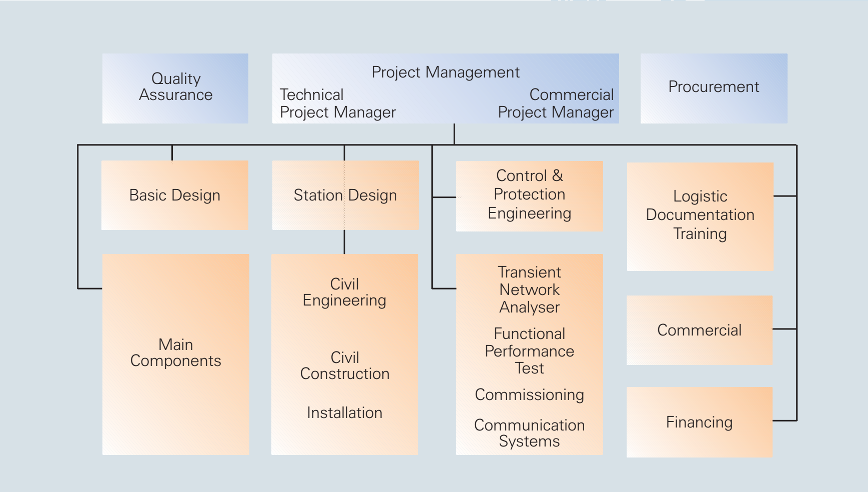


Fig. 7-1: Project organisation plan

7.1.3 Risk reduction

Any risks that could arise due to incorrect deadlines, unclear technical concepts or excessive costs will be recognised early enough by a monitoring system so that counter measures can be taken. This increases contract quality and creates the basis for clear design criteria.

7.1.4 Progress Report

Periodical meetings with subcontractors, in-house control working teams and customer are recorded in progress reports which form an integral part of the quality insurance system.

7.1.5 Scheduling

The hierarchically structured bar-chart schedule is a high-level control tool in project management. The clear structure of sequential processes and parallel activities is crucial for execution of a 24 to 36 month duration, according to the project requirements.

Deadlines for project decisions – especially those of the critical path – can easily be identified enabling the project manager to make up-to date pre-estimates and initiate suitable measures in due time.

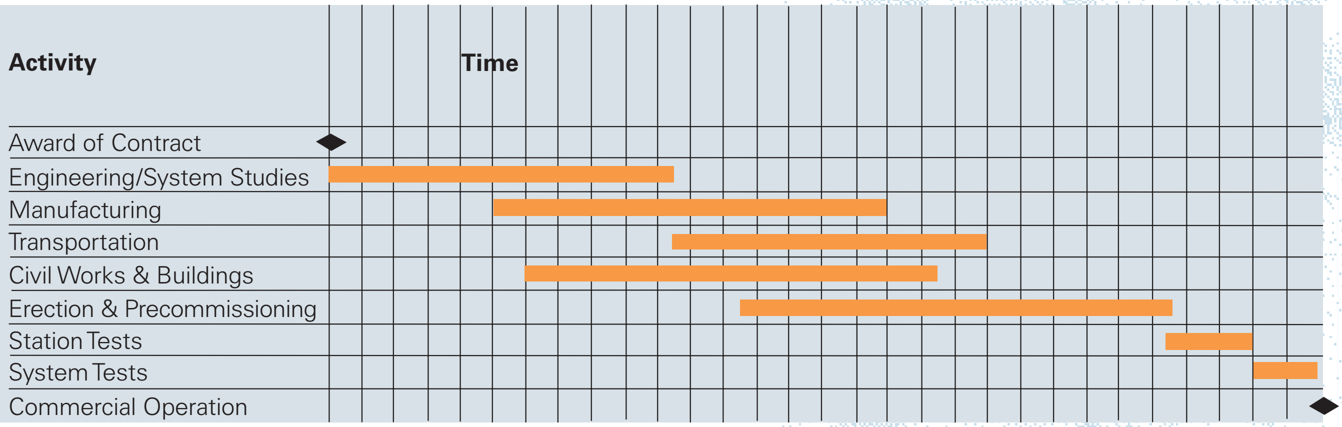


Fig. 7-2: Structured bar-chart timeschedule

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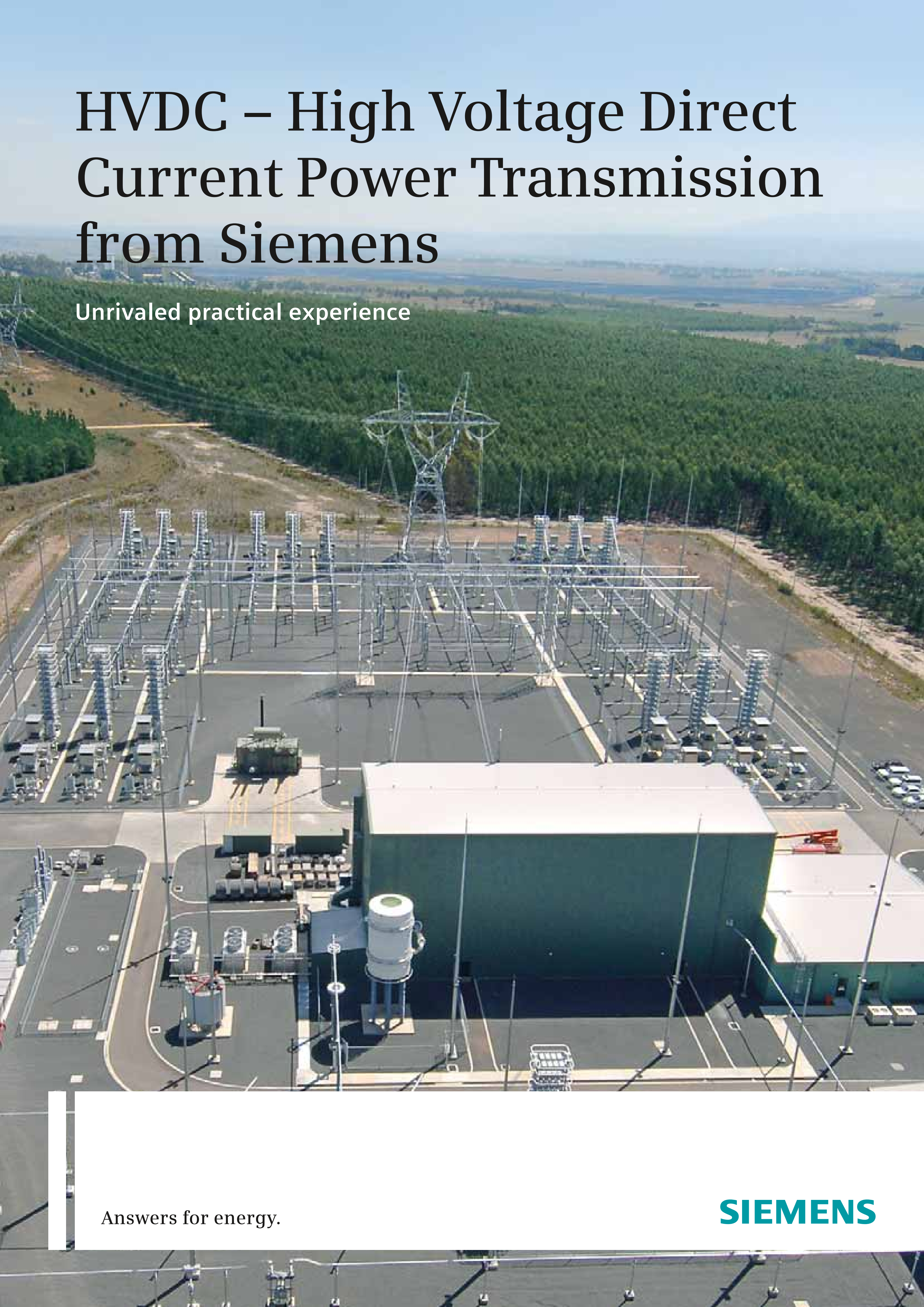
HVDC – High Voltage Direct Current Power Transmission from Siemens

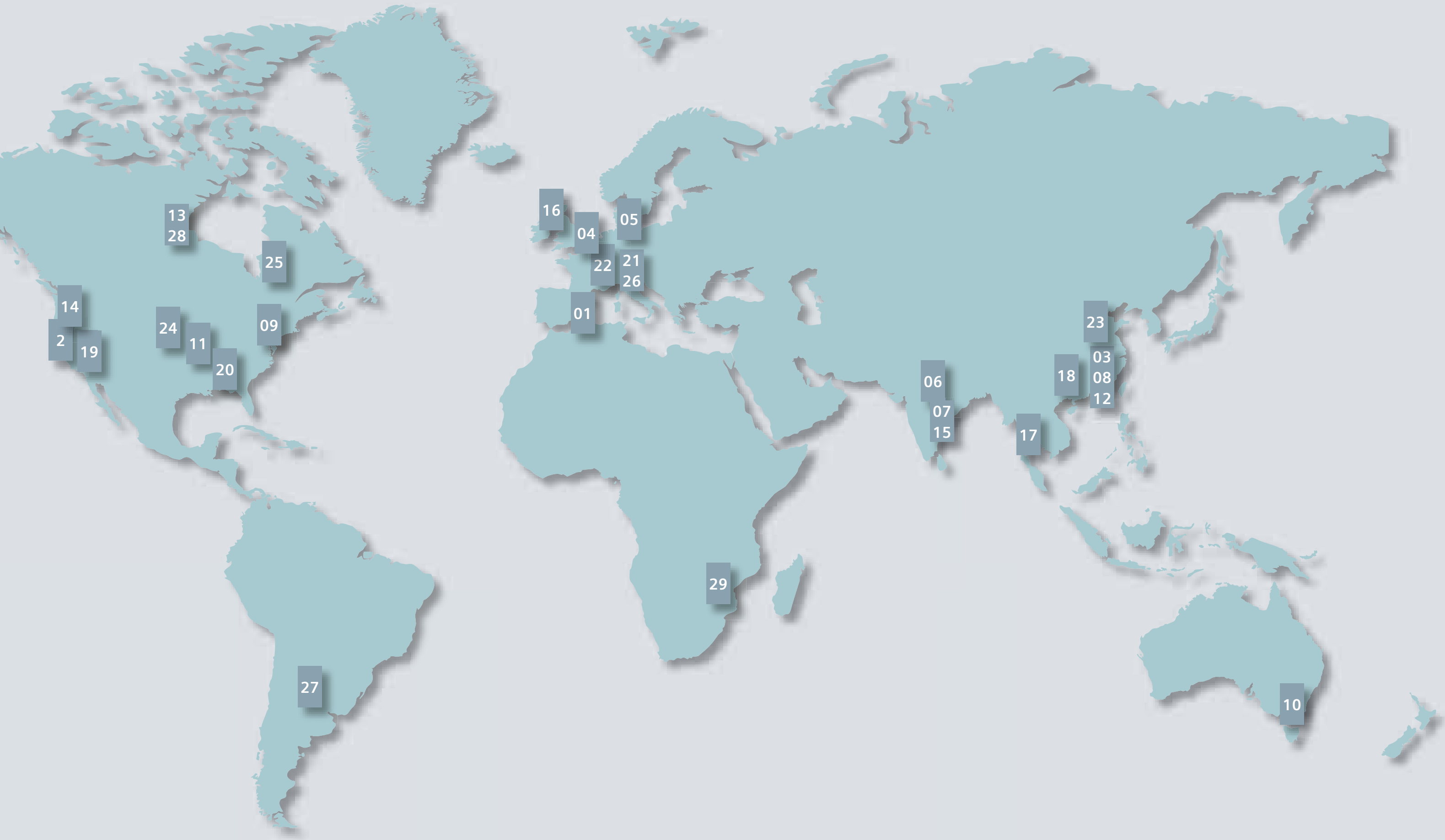
Unrivaled practical experience



Answers for energy.

SIEMENS

HVDC – High Voltage Direct Current Power Transmission is often the best Strategy



In-service date				Page
01	2011	COMETA	Spain	5
02	2010	Trans Bay Cable Project	USA	6
03	2010	Yunnan–Guangdong	China	7
04	2010	BritNed	UK–Netherlands	8
05	2010	Storebælt	Denmark	9
06	2009	Ballia-Bhiwadi	India	10
07	2007	East-South Interconnector II Upgrade	India	11
08	2007	Guizhou-Guangdong II	China	12
09	2007	Neptune	USA	13
10	2006	Basslink	Australia	14
11	2005	Lamar	USA	15
12	2004	Guizhou-Guangdong	China	16
13	2004	Nelson River Bipole 1	Canada	17
14	2004	Celilo	USA	18
15	2003	East-South Interconnector II	India	19
16	2001	Moyle	Northern Ireland/ Scotland	20
17	2001	Thailand/Malaysia	Thailand-Malaysia	21
18	2000	Tianshengqiao-Guangzhou	China	22
19	1995	Sylmar East	USA	23
20	1995	Welsh	USA	24
21	1993	Wien-Südost	Austria	25
22	1993	Etzenricht	Germany	26
23	1989	Gezhouba-Nan Qiao	China	27
24	1987	Virginia Smith	USA	28
25	1984	Poste Châteauguay	Canada	29
26	1983	Dürnrohr	Austria	30
27	1981	Acaray	Paraguay	31
28	1977	Nelson River, Bipole 2	Canada	32
29	1975 1998	Cahora Bassa	South Africa/ Mozambique	33

Direct current – direct success!

AC technology has proved very effective in the field of generation, transmission and distribution of electrical energy. Nevertheless, there are tasks which cannot be performed economically or with technical perfection by this method.
For instance:

- Economical power transmission over very long distances, power transmission via cables
- Power transmission between networks operating asynchronously or at different frequencies
- Input of additional power without increasing the short circuit ratio of the network concerned.

For all these tasks High Voltage Direct Current Power Transmission is not only a realistic technical and economical alternative to AC technology, but also the only possible transmission method.
The plants listed in the following pages show the power ratings and technical standards of our HVDC equipment installed throughout the world.

COMETA, Spain

Red Eléctrica de España signed the contract with Siemens in October 2007 for design, delivery, and construction of 2 x 200 MW HVDC bipole converter stations. Commercial operation is scheduled for July 2011. The COMETA HVDC project, under the responsibility of Red Eléctrica de España, connects the Spanish peninsula with the Ballearic island of Mallorca in order to meet the increasing demand of electric power on the island.

The transmission system is designed as a bipolar interconnector with metallic return conductor. One converter station is located near the city of Valencia on the Spanish peninsula, where an existing power plant will be connected to the HVDC via a HIS Switchgear and HVAC cables (also supplied by Siemens). The other converter station on Mallorca is located at Santa Ponsa near the capital city, Palma de Mallorca. The COMETA submarine link crosses the Mediterranean Sea in a maximum depth of 1,500 meters, has a length of approximately 250 km and will consist of three sea cables, one HV cable per pole and one cable as metallic return conductor.

Customer	Red Eléctrica de España
Project name	COMETA
Location	Spain – Mallorca
Power rating	2 x 200 MW, bipolar
Type of plant	Submarine cable transmission, 250 km
Voltage levels	250 kV DC, 50 Hz, 400 kV/230 kV AC
Type of thyristor	Direct light-triggered (LTT), 8 kV

Trans Bay Cable Project, USA

Trans Bay Cable, LLC, awarded Siemens a contract to construct a submarine High Voltage Direct Current (HVDC) transmission link between San Francisco's city center and a Pacific Gas & Electric substation near Pittsburg, California.
The Trans Bay Cable Project will transmit 400 MW active power and ± 170 Mvar reactive power (statcom function) and is the first order for the innovative HVDC PLUS technology by Siemens. This project is a milestone of the HVDC PLUS technology in terms of providing densely populated areas with new transmission capacity.
Siemens HVDC PLUS System is based on a multilevel Voltage Sourced Converter Technology.
Its innovative design offers technical and economical advantages. HVDC PLUS enhances the performance of the transmission grid, improves reliability, and reduces maintenance costs. HVDC PLUS is the preferred solution in space-constrained environments, as you will find them in San Francisco.

The heart of the HVDC PLUS converter stations is the multilevel converter where the conversion from AC to DC transmission, and vice versa, takes place. In comparison with line-commutated converters based on thyristor technology, the HVDC PLUS system operates with powered semiconductors with turn-on and turn-off capability (IGBT). After commissioning in 2010, the Trans Bay Cable Project is anticipated to meet the California Independent System Operator's (ISO) planning and reliability standards.

Customer	Trans Bay Cable, LLC
Project name	Trans Bay Cable Project
Location	Pittsburg, California, and San Francisco, California
Power rating	400 MW
Type of plant	85 km HVDC PLUS submarine cable
Voltage levels	± 200 kV DC, 230 kV / 138 kV, 60 Hz
Type of semiconductors	IGBT

Yunnan–Guangdong, China

The long-distance transmission system of the Yunnan–Guangdong DC Transmission Project transmits 5,000 MW from the Chuxiong substation in Yunnan to the load center of the Pearl River delta in Guangdong. The contract was awarded in June 2007. Commercial operation of the first 800 kV pole will start in June 2009, the complete bipole will be in operation in June 2010. The system, with a transmission voltage of ±800 kV DC, sets a new dimension in the development of HVDC systems.

The bipolar system uses two series valve groups per pole: one 12 pulse valve group is rated 400 kV; the other is rated 800 kV. Apart from the converter valves, the other major components with insulation levels of 800 kV are the single-phase two-winding converter transformers and air-insulated smoothing reactors. The modular converter groups are equipped with direct light-triggered thyristors with water cooling. The 800 kV equipment in the DC Yard, e.g. bushings, support insulators, switches, and arrester are of composite type with silicone rubber external insulation to offer improved operation under severe environmental conditions. DC harmonic filtering is achieved through triple-tuned filters, whereas for AC harmonic filtering double-tuned filters together with a special low-order filter are used.

Customer	China Southern Power Grid
Project name	Yunnan – Guangdong
Location	Chuxiong City / Yunnan – Zengcheng City / Guangdong
Power rating	5,000 MW, bipolar with series valve groups
Type of plant	Long-distance bipole, 1418 km
Voltage levels	±800 kV DC 525 kV, 50 Hz
Type of thyristor	Direct light-triggered (LTT), 8 kV

BritNed, Great Britain, Netherlands

In May 2007 BritNed Development Limited (owned by the TSOs National Grid International and TenneT) awarded the contract for the BritNed HVDC converter stations to a consortium of Siemens and BAM Civiel BV. The BritNed HVDC transmission system will connect the grid in the UK with the Dutch part of the UCTE grid. It is a 1,000 MW HVDC interconnection across the southern part of the North Sea, linking the 400 kV substations on the Isle of Grain, on the southern bank of the Thames Estuary, and Maasvlakte near Rotterdam.

The HVDC system is designed as a bipole with fast bypass switches without metallic or ground return.
The converter uses quadruple thyristor valves in a double tower configuration, single-phase three-winding converter transformers, air core smoothing reactors, indoor DC switchgear, and double branch AC filters with triple-tuned branches. Commercial operation of the interconnection is about to start in 2010.

Customer	BritNed Development Limited
Project name	BritNed
Location	Isle of Grain on the southern bank of the Thames Estuary in the UK, and Maasvlakte west of Rotterdam in The Netherlands
Power rating	1,000 MW, bipolar
Type of plant	Submarine cable transmission, approximately 200 km
Voltage levels	± 450 kV DC, 400 kV, 50 Hz
Type of thyristor	Direct-light-triggered, 8 kV

Storebælt, Denmark

In May 2007 the Danish TSO, Energinet.dk, awarded the contract for the Storebælt HVDC converters to Siemens.

The Storebælt HVDC transmission system will connect the grid in Jutland/Funen (a part of the UCTE system) with the Zealand Grid, which is a part of the NORDEL system.

It is a 600 MW HVDC interconnection across the Storebælt Strait, linking the 400 kV substations Fraugde near Odense on the island of Funen and Herslev near Kalundborg on the island of Zealand. The HVDC system is designed as a monopole with metallic return. Approximately half of the 56 km DC cable route is a land cable. The converter uses quadruple thyristor valves in a single tower configuration, single-phase three-winding converter transformers, air core smoothing reactors and triple-tuned AC filters. Commercial operation of the interconnection is about to start in 2010.

Customer	Energinet.dk
Project name	Storebælt
Location	The islands Funen (Fyn) and Zealand (Sjælland) in Denmark
Power rating	600 MW, monopolar
Type of plant	Submarine cable transmission, 56 km
Voltage levels	400 kV DC, 400 kV, 50 Hz
Type of thyristor	Direct-light-triggered, 8 kV

Ballia-Bhiwadi, India

In March 2007 Powergrid of India awarded the contract for the largest HVDC system in India to a consortium formed by Siemens and Bharat Heavy Electricals Ltd. (BHEL). The project will transmit power from the Ballia Power Pool in Uttar Pradesh to the Bhiwadi Substation in Rajasthan, only 80 km from Delhi.

The HVDC system will improve the power supply of the fast-growing Delhi metropolitan region without the need for installation additional power plants in this highly urbanized area. The contract includes the engineering, supply, installation, and commissioning, as well as all civil works on a turnkey basis.

Siemens is responsible for the design, offshore supply (including the converter transformer for Ballia station), civil works, and logistic, whereas BHEL takes care of the onshore portion as well as the converter transformers for the Bhiwadi station.

To meet the increasing power demand, the project has to be completed in 33 months, the shortest delivery time for a long-distance transmission system in India.

Customer	Powergrid Corporation of India Ltd.
Project name	Ballia-Bhiwadi
Location	Uttar Pradesh province to Rajasthan province
Power rating	2,500 MW, bipolar
Type of plant	Long-distance transmission, 800 km
Voltage levels	± 500 kV DC, 400 kV, 50 Hz
Type of thyristor	Direct-light-triggered, 8 kV

East-South Interconnector II Upgrade, India

In April 2006 Power Grid Corporation of India Ltd. awarded the contract to Siemens to upgrade the power transmission capacity from 2,000 MW to 2,500 MW on the existing Talcher Kolar HVDC Long Distance Transmission system. Since 2003, the 2,000 MW High Voltage Direct Current (HVDC) System "East-South Interconnector II" links the power generation centre of Talcher in the eastern part of India with the rapidly developing industrial and high-tech area of Bangalore in the south over a line length of nearly 1,400 km. The conventional method to increase the power of a transmission system is to increase the transmission voltage or to increase the current flow through the DC-line. Both measures require extensive and cost-intensive modifications of the system.

Siemens experts have developed an innovative solution not usually used for HVDC systems. With the aid of software systems known as Relative Aging Indication (RAI) and Load Factor Limitation (LFL), a first-time-introduced forced air cooling system for the DC smoothing reactors and other additional measures, it is possible to utilize the overload capacity of the system more effectively without installing additional thyristors connected in series or in parallel to increase the DC transmission voltage or the DC current respectively.

Customer	Powergrid Corporation of India Ltd.
Project name	Upgrade of Talcher Kolar HVDC Project from 2,000 MV to 2,500 MV
Location	Orissa province to Karnataka province
Power rating	2,500 MW, bipolar
Type of plant	Long-distance transmission, 1,450 km
Voltage levels	± 500 kV DC, 400 kV, 50 Hz
Type of thyristor	Electrically-triggered-thyristor, 8 kV (100 mm)

Guizhou-Guangdong II, China

The DC Transmission Project (the long-distance transmission system of the Guizhou-Guangdong II line ±500 kV) transmits 3,000 MW power from the Xingren substation in the Guizhou Province of Southwest China to the load center of Shenzhen in the Guangdong Province. The system has a long-term overload capability of up to 115%. Power transmission in the reverse direction is also possible.

The project is carried out in cooperation with Chinese partners supported by Siemens. The bipolar system is designed for a ceiling suspended 12-pulse converter bridge arrangement with single-phase two-winding converter transformers and oil-insulated smoothing reactors. The 500 kV DC converter groups of modular design are equipped with direct light-triggered thyristors with water cooling. Most of the DC equipment is provided with composite housings improving the performance of operation under severe environmental conditions.

For harmonic filtering triple tuned AC and DC filters are used. The design considers the installation at 1450 m above sea level (Xingren converter station). The interconnection of the neutrals of both stations is implemented by means of ground electrodes.

The contract was awarded in May 2005. Execution time of the first pole is 25 months and that of the bipole is 31 months.

Customer	China Southern Power Grid
Project name	Guizhou-Guangdong II Line ±500 kV DC Transmission Project
Location	Xingren/Guizhou – Shenzhen/Guangdong
Power rating	3,000 MW, bipolar
Type of plant	Long-distance bipole, 1,225 km
Voltage levels	±500 kV DC, 525 kV, 50 Hz
Type of thyristor	Direct-light-triggered, 8 kV

Neptune RTS, USA

The Neptune HVDC project connects the TSO Long Island Power Authority to the competitive PJM market and provides power to a fast-growing load center on Long Island. The system is a monopolar cable transmission link with a DC voltage of 500 kV and a continuous power transmission rating of 660 MW. The cable stretches from First Energy Inc.'s substation in Sayreville, N.J., to Uniondale, N.Y.-based LIPA's Newbridge Road substation in Levittown. Siemens, as the leader of the consortium for this turnkey project, was responsible for the installation of two converter stations. Furthermore, Siemens is to operate the link for a five-year period. The consortium partner Prysmian (formerly Pirelli) delivered and installed the cable package including a 82 km DC submarine cable section from New Jersey to the landfall at Jones Beach followed by a 23 km DC land cable section to the Converter Station as well as the AC cable connections from the two converter stations to the grid. The project was developed by Neptune RTS over a period of several years. The EPC contract was awarded on July 15th, 2005. Execution time of the project was 24 months.

Customer	Neptune RTS
Project name	Neptune RTS
Location	USA/New Jersey – New York
Power rating	660 MW, monopolar
Type of plant	Submarine cable transmission, 105 km
Voltage levels	500 kV, 230/345 kV, 60 Hz
Type of thyristor	Direct-light-triggered, 8 kV

Basslink, Australia

The Basslink cable link, which went into operation in 2006, represents the first interconnection between the states of Tasmania and Victoria. Both states benefit from this link, which operates in both directions. Tasmania relies entirely on hydroelectric plants to generate electricity; Basslink allows the import of base load from Victorian coal-fired power plants, thus improving supply reliability in periods of drought. On the other side, Victoria is able to improve its peak load supply with green energy from Tasmania. Tasmania's first-ever access to the National Energy Market (NEM) has also increased competition within Australia. The transmission system is designed as a monopolar interconnector with metallic return. As consortium leader, Siemens augmented two existing AC substations and provided 5 km of AC overhead line, the HVDC converter stations, and 66 km of DC overhead line. Basslink now represents one of the longest submarine power links in the world, with a submarine cable length of approximately 295 km that crosses the Bass Strait. The EPC contract was awarded in the year 2000, and authorities approved the project in the second half of 2002 after extensive environmental impact studies.

Customer	National Grid Australia
Project name	Basslink Interconnector
Location	Loy Yang/Victoria to George Town/Tasmania
Power rating	500 MW continuous, up to 626 MW overload for 8 hours/day
Type of plant	Submarine cable transmission, 295 km
Voltage levels	400 kV DC, 500 kV 50 Hz (Victoria) 220 kV 50 Hz (Tasmania)
Type of thyristor	Direct-light-triggered, 8 kV

Lamar, USA

In February 2003 Xcel Energy awarded the contract to Siemens for the design, procurement, construction, and commissioning of the Back-to-Back DC Converter station located in Lamar, Colorado. The tie connects Xcel Energy's Southwestern Public Service Company system in the East (345 kV AC) with its Public Service Company of Colorado system in the West (230 kV AC), and has a bidirectional power transfer capability of 210 MW (nominal).

As one of its main features, the converter station provides continuously adjustable voltage control on the weak AC System.

The Eastern part and the Western part of the United States is not electrically synchronized. The dividing line is roughly down the eastern borders of Montana, Wyoming Colorado, and New Mexico. The Lamar project has been commercial operation since January 2005. The Back-to-Back DC converter station is highly cost-efficient due to a new grounding concept of the DC circuit. This concept allows the use of standard distribution transformers instead of special HVDC converter transformers. Standardized components result in shorter delivery time, and allow for high local manufacturing content.

Customer	Xcel Energy
Project name	Lamar
Location	Lamar/Colorado/USA
Power rating	210 MW, continuous
Type of plant	Back-to-back tie
Voltage levels	63.6 kV DC 230 kV AC, 60 Hz (West Lamar/Colorado) 345 kV AC, 60 Hz (Easy Finney/Kansas)
Type of thyristor	Direct-light-triggered, 8 kV

Guizhou-Guangdong, China

The HVDC long-distance transmission system of Gui-Guang transmits 3,000 MW of power from the Anshun substation in Guizhou Province in southwest China to the Zhaoqing converter station in Guangdong Province near the load center of Guangzhou. It is a bipolar system, each pole comprising a 12-pulse converter bridge suspended from the ceiling. The thyristors are water-cooled and direct-light-triggered. The converter transformers are of the single-phase two-winding type. Triple-tuned filters are used for filtering harmonics on the DC- and AC-side of the converters. The smoothing reactors are of the oil-immersed type. The contract was awarded in October 2001. Commercial operation started in October 2004 (six months ahead of scheduled time).

Customer	State Power South Company (SPSC)
Project name	Gui-Guang
Location	Guizhou-Guangdong
Power rating	3,000 MW, bipolar
Type of plant	Long-distance transmission, 980 km
Voltage levels	± 500 kV DC 525 kV, 50 Hz
Type of thyristor	Direct-light-triggered, 8 kV

Nelson River Bipole 1, Canada

In 2002 Siemens received the contract to replace 36 mercury arc valves (MRVs) with thyristor valves. Bipole 1 of the Nelson river scheme had been in operation since 1970. Both poles were equipped with mercury arc valves designed for service life of 20 years. The old valves of Bipole 1, Pole 1 were replaced by thyristor valves 10 years ago. By using the best valves as spare parts for Pole 2, operation for 10 more years was possible. In 2001 Manitoba Hydro decided to also replace the MRVs of Pole 2 with thyristor valves to increase the reliability of the whole scheme. To minimize the outage time of this highly utilized scheme, replacement was performed in 3 lots.

For each lot 12 thyristor valves and 2 cooling units as well as new surge arresters are supplied.

The overall completion time for the replacement was 27 months with a delivery time for the first lot of 13 months. Siemens delivered light-triggered thyristors, the same type as supplied for the Moyle Interconnector and the Celilo project. For future upgrading of the system the thyristor valves are rated for 500 kV with 2,000 A nominal current.

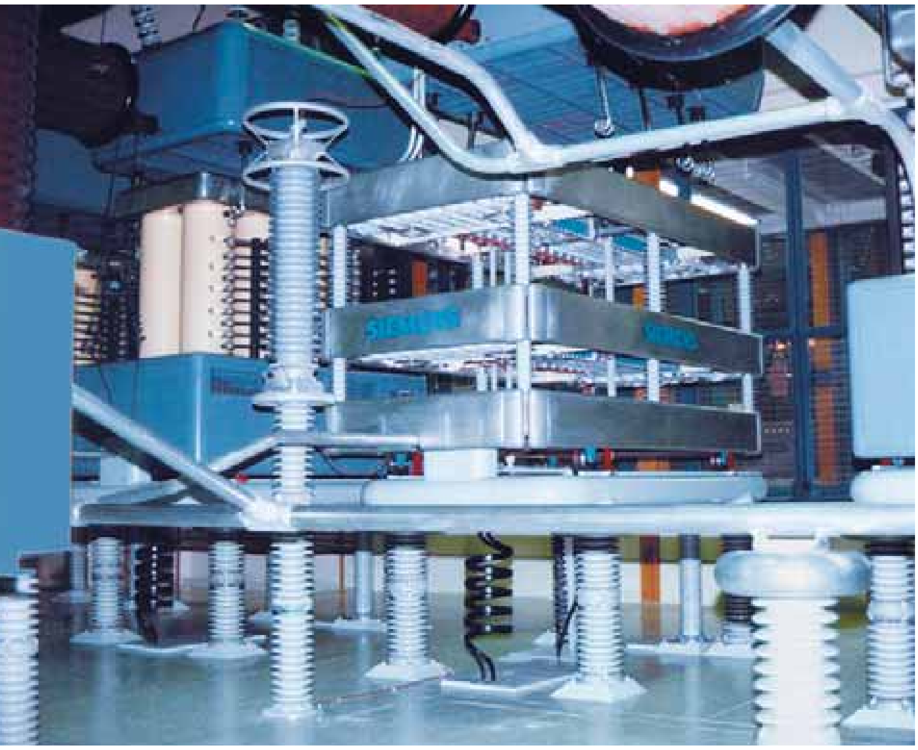
To meet the customer’s demand for a short outage time the thyristor valves are designed to fit on to the existing support structure and therefore no time-consuming changes involving civil works are necessary.

Customer	Manitoba Hydro (Winnipeg)
Project name	Bipole 1, Pole 2 Valve Replacement
Location	Radisson Converter Station on Nelson River Dorsey Converter Station near Winnipeg, both in Manitoba, Canada
Power rating	900 MW (1,000 MW future)
Type of plant	Long-distance transmission, 900 km
Voltage levels	450 kV DC (500 kV future) 230/138 kV, 60 Hz
Type of thyristor	Direct-light-triggered, 8 kV

Celilo, Mercury Arc Valve Replacement, USA

In December 2000, Bonneville Power Administration (BPA) in Portland, Oregon, USA had to decide how to proceed with the Celilo Converter Station which was 30 years old meanwhile, and considering that the Pacific Intertie is a major contributor to satisfying California's electrical energy needs. The critical components were the mercury arc valves: they had been designed for a service life of 20 years; they require high maintenance efforts, are very unreliable, and the manufacturer had stopped supplying spare parts long ago. Based on the decision, BPA awarded Siemens a contract for the supply of 36 HVDC thyristor valves with direct-light-triggered thyristors for the Celilo Converter Station of the Pacific Intertie, to replace the mercury arc valves – representing a converter rating of 1,600 MW. The delivery in three phases was completed within 20 months.
In addition, all cooling towers in the 3,100 MW converter station were replaced by dry-type cooling towers. In 1997 Siemens provided BPA with a thyristor valve including the newly developed technology of direct-light-triggered thyristors for commercial demonstration during a period of two years. It was replacing a mercury arc valve. Due to the excellent performance, BPA purchased the valve already after 11 months of operation. It has been in service ever since without any fault or failure.

Customer	Bonneville Power Administration (BPA)
Project name	Celilo Mercury Arc Replacement Project
Location	The Dalles, Oregon, USA
Power rating	3,100 MW, bipolar
Type of plant	Long-distance transmission
Voltage levels	± 400 kV DC 230 kV, 60 Hz
Type of thyristor	Direct-light-triggered, 8 kV



East-South Interconnector II, India

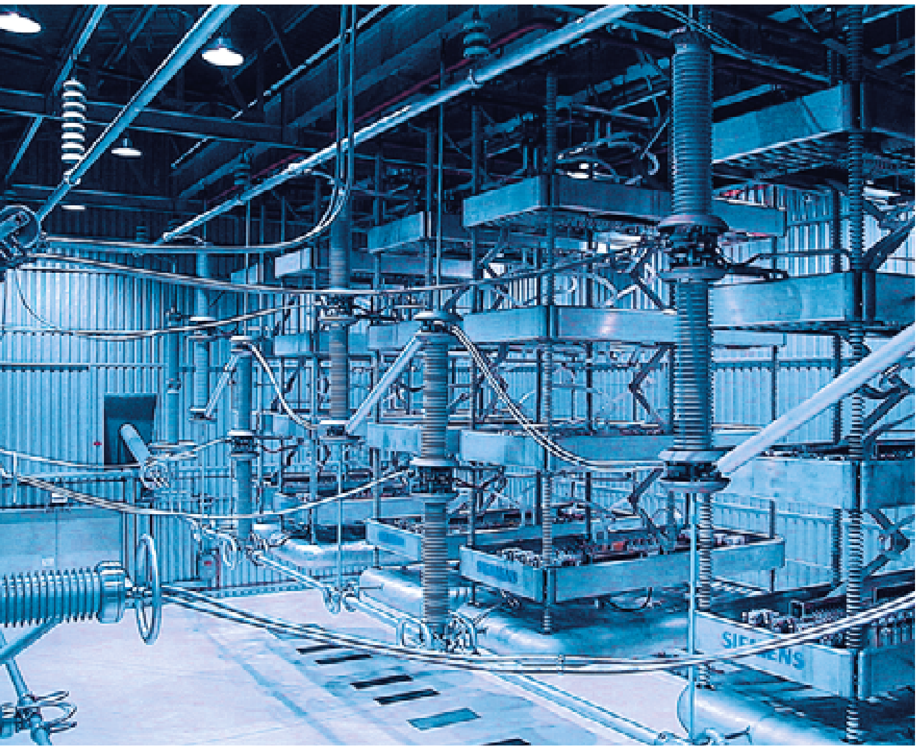
In March 2000 Siemens received an order for a long-distance HVDC transmission project from the Power Grid Corporation of India Limited. From now on power is transmitted from the eastern region (Orissa province) to the southern part (Karnataka province) of the subcontinent by means of a bipolar HVDC system, thus integrating these two regional asynchronous networks into the national grid, ensuring a reliable and flexible power transfer nationwide. This is the sixth HVDC project in India, the largest so far regarding rated transmission power and transmission distance. Commercial operation started in 2003.

Customer	Power Grid Corporation of India Ltd.
Project name	East-South Interconnector II
Location	Orissa province to Karnataka province
Power rating	2,000 MW, bipolar
Type of plant	Long-distance transmission, 1,450 km
Voltage levels	±500 kV DC 400 kV, 50 Hz
Type of thyristor	Electrically-triggered-thyristor, 8 kV (100 mm ∅)

Moyle, Northern Ireland/Scotland

The Moyle Interconnector Project provides a vital link in electricity supply, enhancing both security and competition in the emerging market of Northern Ireland. The configuration of the transmission system is two monopolar submarine HVDC links operating in parallel on the AC systems. Each pole is rated 250 MW in both directions at 250 kV DC. For the first time in a commercial HVDC system, the converter stations are equipped with the latest achievement in high-voltage semiconductor technology: direct-light-triggered thyristors with integrated overvoltage protection. By introducing this new technology, the number of electrical parts in the HVDC thyristor valve is considerably reduced, resulting in better reliability and longer maintenance intervals. The contract for the Moyle Interconnector turnkey supply of the converter stations was awarded in September 1999. Taking-over certificate by the customer was issued in November 2001.

Customer	Moyle Interconnector Ltd. (MIL) Northern Ireland
Project name	Moyle Interconnector
Location	Northern Ireland, Scotland
Power rating	2 x 250 MW
Type of plant	Submarine cable transmission, 64 km
Voltage levels	2 x 250 kV, DC 275 kV, 50 Hz
Type of thyristor	Direct-light-triggered, 8 kV



Thailand/Malaysia

This HVDC long-distance transmission system interconnecting the 230 kV AC network of Thailand with the 275 kV AC network of Malaysia is implemented in the first stage as a 300 MW monopolar metallic return scheme. As a turnkey project, complete HVDC system design and network integration, delivery of the converter stations, AC switchgear, and the interconnecting 300 kV DC overhead line was included in Siemens' scope of supply. Commercial operation started in 2001.

Customer	Electricity Generating Authority of Thailand (EGAT) Tenaga Nasional Berhad (TNB)
Project name	Thailand-Malaysia
Location	Khlong Ngae/Gurun
Power rating	300 MW, monopolar
Type of plant	Long-distance transmission, 110 km
Voltage levels	300 kV DC EGAT: 230 kV,50 Hz TNB: 275 kV, 50 Hz
Type of thyristor	Electrically-triggered-thyristor, 8 kV (100 mm ∅)

Tianshengqiao–Guangzhou, China

The HVDC long-distance transmission system Tian-Guang carries 1,800 MW of electrical power from the hydropower plant Tianshengqiao in southwest China to the load center of Guangzhou in the south. It is a bipolar system, each pole comprising a 12-pulse converter valve group, with the valve towers hanging from a special ceiling construction. The thyristors are water-cooled. The transformers are of the single phase three-winding type with bushings protruding into the valve hall. Active DC filters are implemented in this system for absorption of DC harmonics to avoid interference on neighboring communication lines. The contract was awarded in 1997; commercial operation started in 2000.

Customer	State Power South Company (SPSC)
Project name	Tian-Guang
Location	Tianshengqiao-Guangzhou
Power rating	1,800 MW, bipolar
Type of plant	Long-distance transmission, 960 km
Voltage levels	± 500 kV DC 230 kV, 50 Hz
Type of thyristor	Electrically-triggered-thyristor, 8 kV

Sylmar East Valve Reconstruction, USA

The Pacific HVDC Intertie started its operation in 1970 at 1,440 MW. By addition of series and parallel connected converters it was later expanded to a rating of 3,100 MW. When a disastrous fire had destroyed the thyristor valves of converter 1 at Sylmar East Converter Station in 1993, the Los Angeles Department of Water and Power was under pressure to restore reliable power supply to the energy-hungry region. Siemens was awarded the reconstruction in August 1994, due to the short delivery time, use of fire-retardant valve material (UL94 VO), the anticorrosion cooling system concept, and the excellent seismic performance of the valves (0.5 g horizontal). The installation was finished in September 1995. The scope of supply comprises one complete 12-pulse converter, including DC hall equipment, and an advanced monitoring and alarm system.

Customer	Los Angeles Department of Water and Power, California, USA (LADWP)
Project name	Sylmar East Valve Reconstruction
Location	Sylmar Converter Station East, Los Angeles
Power rating	550 (825) MW, bipolar
Type of plant	Long-distance transmission, approx. 1,200 km
Voltage levels	500 kV DC 230 kV, 60 Hz
Type of thyristor	Electrically-triggered-thyristor, 8 kV

Welsh, USA

The back-to-back tie links the two different networks of the Energy Reliability Council of Texas (ERCOT grid) with the Southwest Power Pool (SPP grid) of the eastern US system. The Welsh Converter Station allows an additional power transfer to the existing connection (at Oklaunion) between the two networks. The arrangement and the design of the station are comparable to Etzenricht. The reliable and proven converter technology of Etzenricht, along with the same control and protection systems, is therefore used.

Customer	American Electric Power, Ohio, USA (AEP)
Project name	Welsh HVDC Converter Station
Location	Texas, Titus County near Mount Pleasant
Power rating	600 MW
Type of plant	Back-to-back tie
Voltage levels	170 kV DC 345/345 kV, 60/60 Hz
Type of thyristor	Electrically-triggered-thyristor, 5.5 kV

Wien-Suedost, Austria

The back-to-back tie links the Austrian UCPTE network with the Hungarian and, hence, the RGW network. The modular water-cooled air-insulated valves are of a new, compact, and universal design. The rectifier and inverter are in 12-pulse connection and are accommodated in a building along with the bushings of the converter-transformers and the smoothing reactors. This HVDC plant southeast of Vienna was put in operation in July 1993.

Customer	Österreichische Elektrizitätswirtschafts Aktiengesellschaft (Verbundgesellschaft, VG)
Project name	GK-Wien-Südost (GK-SO)
Location	Southeast of Vienna, Austria
Power rating	600 MW
Type of plant	Back-to-back tie
Voltage levels	145 kV DC 380/380 kV, 50/50 Hz
Type of thyristor	Electrically-triggered-thyristor, 5.5 kV

Etzenricht, Germany

The back-to-back tie links the two different networks of the Czech Republic and the Federal Republic of Germany, that is, the Western European network UCPTE with the Eastern European network RGW. The HVDC plant considerably improved the availability of electrical energy in both countries and, at the same time, reduced the need for investment in reserve generating capacity. Standardized modular converters allow for much smaller valve halls than previously permitted and therefore offer major advantages in terms of economy. The converter transformers are arranged outside the valve hall. Their insulating bushings for connection to the thyristors are led directly into the converter hall. The HVDC plant in Etzenricht near Weiden/Oberpfalz was commissioned in June 1993.

Customer	E.ON AG Munich, Germany
Project name	Etzenricht
Location	Etzenricht, near Weiden/Oberpfalz
Power rating	600 MW
Type of plant	Back-to-back tie
Voltage levels	160 kV DC 380/380 kV, 50/50 Hz
Type of thyristor	Electrically-triggered-thyristor, 5.5 kV

Gezhouba-Nan Qiao, China

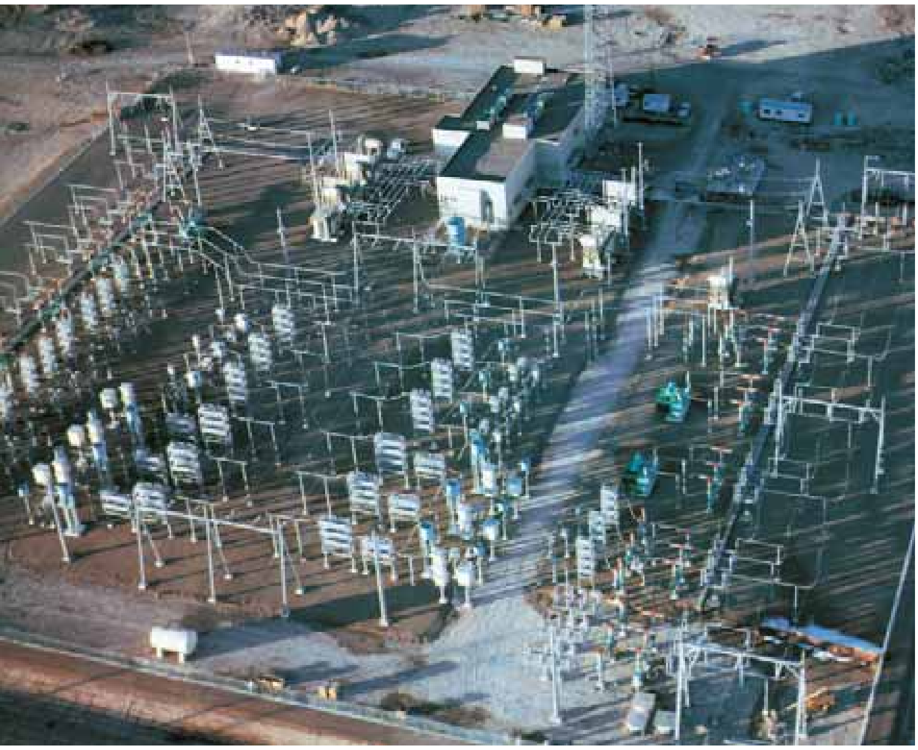
The Gezhouba-Nan Qiao HVDC plant transmits electric power from the hydroelectric plant in Gezhouba in the Hubei province, central China, to the Shanghai conurbation. The power transmission system is bipolar, each pole consisting of a 12-pulse converter valve group. The valve towers are suspended from a special structure on the ceiling of the valve hall. The single-phase three-winding converter-transformers and their bushings project into the hall, where the star delta connections are made. The thyristors are water-cooled. Commercial operation started in 1989 (Pole 1), and in 1990 (Pole 2).

Customer	China National Technical Import & Export Corporation (CNTIC)
Project name	Ge-Nan
Location	Rectifier station in Gezhouba (Central China), Inverter station in Nan Qiao (about 40 km from Shanghai)
Power rating	1,200 MW, bipolar
Type of plant	Long-distance transmission, about 1,000 km
Voltage levels	±500 kV DC 525/230 kV, 50/50 Hz
Type of thyristor	Electrically-triggered-thyristor, 5.5 kV

Virginia Smith, USA

The HVDC back-to-back tie at Virginia Smith Converter Station in Nebraska, USA, links the asynchronous networks in the East of the United States with those in the West. The station is controlled via the WAPA communications system from the load control center in Loveland, Colorado, 150 miles away. 200 MW can be transmitted in either direction. Despite power input in networks with low power ratings, voltage stability is assured within narrow limits. Temporary overvoltage limiters can be switched in to keep transient overvoltages within 1.25 p.u. The HVDC plant has been in operation since December 1987.

Customer	Western Area Power Administration (WAPA)
Project name	Virginia Smith Converter Station
Location	Sidney, Nebraska, USA
Power rating	200 MW
Type of plant	Back-to-back tie
Voltage levels	50 kV DC 230/230 kV, 60/60 Hz
Type of thyristor	Electrically-triggered-thyristor, 4.52 kV



Poste Châteauguay, Canada

The Poste Châteauguay back-to-back tie effects the exchange of power between Canada (Hydro Quebec) and the USA (NYPA). The plant comprises two poles and has a power rating of 500 MW per pole. Overload operation up to 1,200 MW is possible. Each of the two poles is accommodated in a valve hall with two 12-pulse groups. One group is connected with the 120 kV system in the USA, and the other with the 315 kV system in Canada. The project, which was jointly awarded to BBC and Siemens, was completed on July 1, 1984, after a construction time of about one year.

Customer	Hydro Quebec, Montreal, Canada
Project name	Poste Châteauguay
Location	Beauharnois, Quebec, Canada
Power rating	2 x 500 MW
Type of plant	Back-to-back tie
Voltage levels	145 kV DC 120/315 kV, 60/60 Hz
Type of thyristor	Electrically-triggered-thyristor, 4.5 kV

Dürnrohr, Austria

The HVDC back-to-back tie between Austria and the Czech Republic linked the then-asynchronous networks of Western and Eastern Europe. The contract was placed in 1980. The thyristor valves are water-cooled and air-insulated; for the first time, high-voltage thyristors with a wafer diameter of 100 mm were used. The system consists of two 12-pulse groups in a common building and the transformers and smoothing reactors which are installed outdoors, with DC-side bushings protruding through the walls. Siemens, partnering with the German HVDC Group, supplied all thyristor modules and the station control system. Commercial operation started in 1983.

Customer	Österreichische Elektrizitätswirtschafts Aktiengesellschaft (Verbundgesellschaft, VG)
Project name	Dürnrohr
Location	Dürnrohr, near Zwentendorf, Austria
Power rating	550 MW
Type of plant	Back-to-back tie
Voltage levels	145 kV DC 380/380 kV, 50/50 Hz
Type of thyristor	Electrically-triggered-thyristor, 4.2 kV

Acaray, Paraguay

The HVDC back-to-back tie in Paraguay links the Brazilian 60 Hz network with the Paraguayan 50 Hz network. In times of drought and low output from the hydropower plants, Paraguay imports power from Brazil, while power can be exported to Brazil in times of water surplus. The frequency regulation of the HVDC back-to-back tie also helps stabilize the Paraguayan network frequency to 50 Hz. Commercial operation started in 1981.

Customer	A.N.D.E.
Project name	Acaray
Location	Paraguay
Power rating	55 MW
Type of plant	Back-to-back tie
Voltage levels	25 kV DC 220/138 kV, 50/60 Hz
Type of thyristor	Electrically-triggered-thyristor, 4.2 kV

Nelson River, Bipole 2, Canada

The power plants on the Nelson and Churchill Rivers in the north of Manitoba, Canada, generate more than 50 % of the demand of this province: the double-bipolar HVDC link supplies the power to the load centers in the south of the province. Bipole 2 is the first HVDC system using highly efficient water cooling for the thyristor valves – a technology that has since become the industry standard. Siemens, partnering in the German HVDC Group, supplied all thyristor modules and the 500 kV smoothing reactors. Commercial operation started in 1977 with stage 1; the project was completed in 1985 with stage 3.

Customer	Manitoba Hydro (Winnipeg)
Project name	Nelson River, Bipole 2
Location	Henday Converter Station near Nelson River Dorsey Converter Station near Winnipeg both in Manitoba, Canada
Power rating	1,800 MW (summer) 2,000 MW (winter), bipolar
Type of plant	Long-distance transmission, about 1,000 km
Voltage levels	± 500 kV DC 230/230 kV, 60/60 Hz
Type of thyristor	Electrically-triggered-thyristor, 3.2 kV

Cahora Bassa, South Africa/Mozambique

The Cahora Bassa HVDC system is used to transmit the power generated in a hydroelectric plant on the Sambesi river in Mozambique to South Africa. The contract for the HVDC system, the dam, and the powerhouse was awarded to the ZAMCO consortium, including the German HVDC Group (AEG, BBC, Siemens). Cahora Bassa is the first HVDC contract placed that used thyristor valves. An outdoor, oil-cooled, and oil-insulated design was used. Commercial operation started in 1975 with phase 1; the system was completed in 1979 with phase 3. During the 1980s the transmission line was heavily damaged by terrorist attack and the system was down until the nineties, when Siemens undertook the refurbishment of the converter stations. Besides the careful restoration of the main equipment, the complete DC control was exchanged by a fully digital, computerized system including a modern Human-Machine Interface (HMI). The new system increases the availability and reliability of the complex HVDC system considerably in terms of operator guidance. The most powerful HVDC transmission link in Africa has been back in operation since 1998.

Customer	1. HCB, Lisbon, Portugal 2. ESCOM, Johannesburg, South Africa
Project name	Cahora Bassa
Location	Songo, Mozambique Apollo, South Africa
Power rating	1,920 MW, bipolar
Type of plant	Long-distance transmission, 1,456 km
Voltage levels	±533 kV DC 220/275 kV, 50/50 Hz
Type of thyristor	Electrically-triggered-thyristor, 1.65 kV/2.5 kV

Siemens AG
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HVDC PLUS –
Basics and Principle of Operation

Answers for energy.

SIEMENS

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HVDC PLUS – Basics and Principle of Operation

M. Davies, M. Dommaschk, J. Dorn, J. Lang, D. Retzmann, D. Soerangr

0. Preface

This special edition summarizes prospects and technology issues of the latest developments in voltage-sourced converters for Advanced High Voltage DC transmission systems in the range of medium power applications [4–10, 16-19, 21, 22, 24-27].

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1. Introduction

Environmental constraints will play an important role in the power system developments [1–2, 18]. However, regarding the system security, specific problems are expected when renewable energies, such as large wind farms, have to be integrated into the system, particularly when the connecting AC links are weak and when sufficient reserve capacity in the neighboring systems is not available [3]. In the future, an increasing part of the installed capacity will be connected to the distribution levels (dispersed generation), which poses additional challenges to the planning and safe operation of the systems. Power electronics will be required to control load flow, to reduce transmission losses and to avoid congestion, loop flows and voltage problems [4–6, 12].

HVDC (High Voltage Direct Current) systems and FACTS (Flexible AC Transmission Systems) provide essential features to avoid technical problems in the power systems; they increase the transmission capacity and system stability in a very efficient way, and assist in prevention of cascading disturbances [11–27].

HVDC systems and FACTS controllers based on line-commutated converter technology have a long and successful history. Thyristors are the key components of this converter topology and they have achieved a high degree of maturity due to their robust design and high reliability. It is, however, worth mentioning that line-commutated converters have some technical restrictions. Particularly the fact that the commutation within the converter is driven by the AC voltages requires proper conditions of the connected AC system, such as a minimum short-circuit power.

Power electronics with self-commutated converters, such as Voltage-Sourced Converters (VSC), can overcome these limitations and they provide additional technical features. In many applications, VSC have become a standard of self-commutated converters and will be used increasingly more often in transmission and distribution systems in the future. VSCs do not require any "driving" system voltage – they can build up a three-phase AC voltage via the DC voltage (Black-Start capability). So, in the case of DC transmission, HVDC PLUS with VSCs is the preferred technology for interconnection of islanded grids, such as offshore wind farms, with the power system.

So far, VSCs for HVDC and FACTS applications are mostly based on two or three-level converters. It is, however, a fact that multilevel VSCs provide advantages with respect to the dynamic performance and harmonic impact. For these reasons, a new Modular Multilevel Converter technology (MMC), referred to as HVDC PLUS and SVC PLUS, has been developed, which provides significant benefits for high voltage applications.

2. HVDC and FACTS Technologies

HVDC systems and FACTS controllers based on line-commutated converter technology (LCC) have a long and successful history. Thyristors have been the key components of this converter topology and have reached a high degree of maturity due to their robust technology and their high reliability. HVDC and FACTS with LCC use power electronic components and conventional equipment which can be combined in different configurations to switch or control reactive power, and to convert the active power. Conventional equipment (e.g. breakers, tap-changing transformers) has very low losses, but the switching speed is relatively low. Power electronics can provide high switching frequencies up to several kHz which, however, leads to an increase in losses.

Fig. 1 indicates the typical losses depending on the switching frequency [16]. It can be seen that due to the low losses, line-commuted Thyristor technology is the preferred solution for bulk power transmission, today and in the future.

It is, however, worth mentioning that line-commutated converters have some technical restrictions. Particularly the fact that the commutation within the converter is driven by the AC voltages requires proper conditions of the connected AC system, such as a minimum short-circuit power.

A comparison of the different HVDC technologies is depicted in Fig. 2.

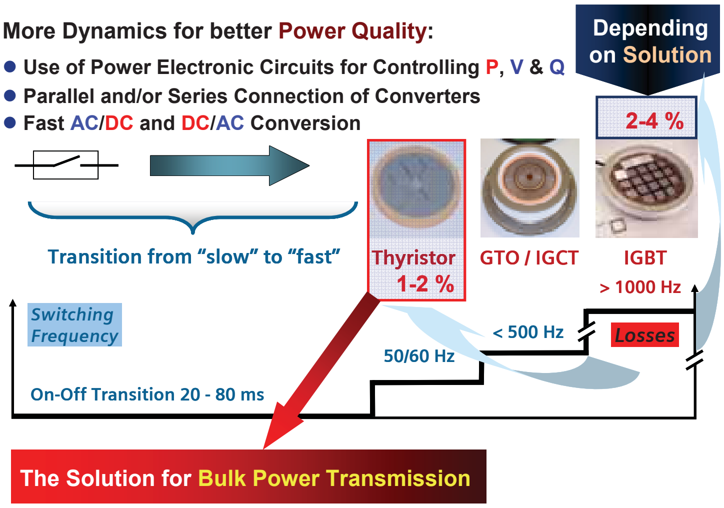
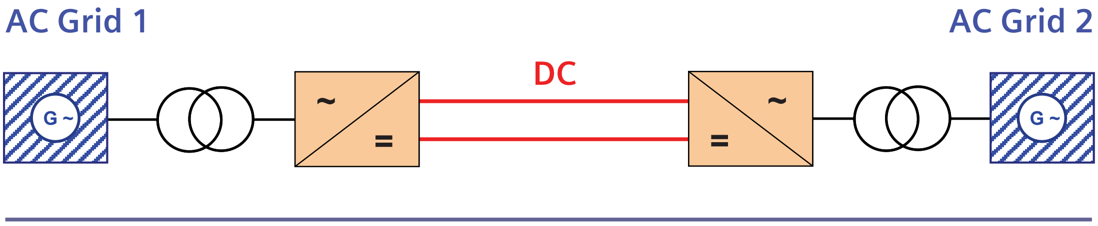


Fig. 1: Power Electronics for HVDC and FACTS – Transient Performance and Losses



HVDC "Classic"	HVDC PLUS
Line-Commutated Current-Sourced Converter (LCC / CSC)	**Self-Commutated Voltage-Sourced Converter (SCC / VSC)**
Thyristors with Turn-on Capability only	**Semiconducting Switches with Turn-On and Turn-Off Capability, e.g. IGBTs**

Fig. 2: HVDC "Classic" and HVDC PLUS – Technologies

2.1 Voltage-Sourced Converters

Power electronics with self-commutated converters can cope with the limitations mentioned above and provide additional technical features. In DC transmission, an independent control of active and reactive power, the capability to supply weak or even passive networks and lower space requirements are some of the advantages. In many applications, the VSC has become a standard of self-commutated converters and will be used more often in transmission and distribution systems in the future. Voltage-Sourced Converters do not require any "driving" system voltage; they can build up a 3-phase AC voltage using the DC voltage. This kind of converter uses power semiconductors with turn-off capability such as IGBTs (Insulated Gate Bipolar Transistors).

The benefits of VSC technology are depicted in Fig. 3. Figs. 4 and 5 show the P and Q outputs of HVDC "Classic" and HVDC PLUS.

Grid Access for weak AC Networks

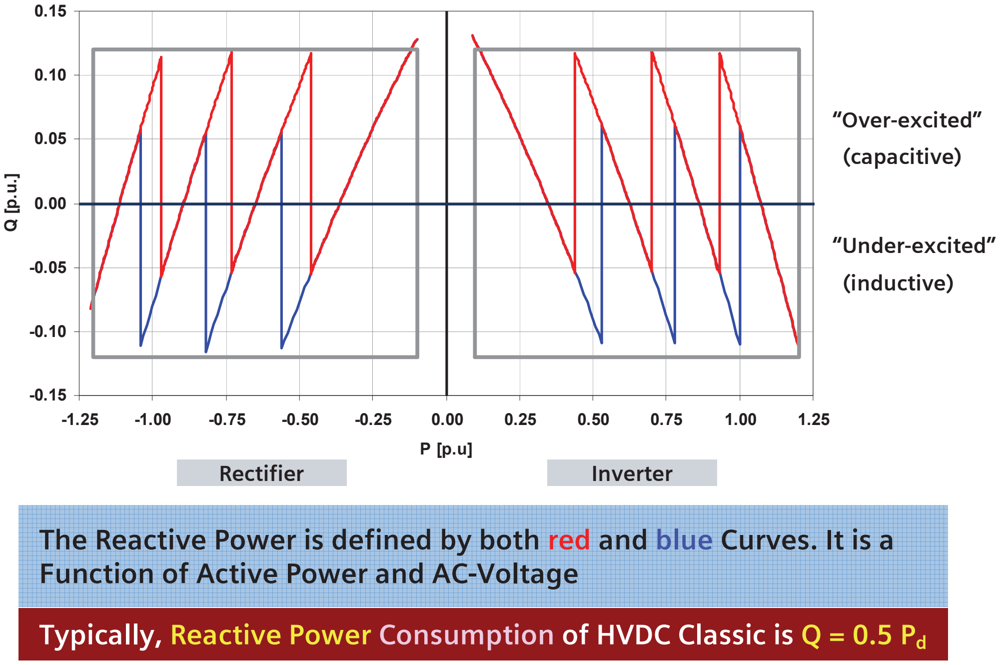
Independent Control of Active and Reactive Power

Supply of passive Networks and Black-Start Capability

High dynamic Performance

Low Space Requirements

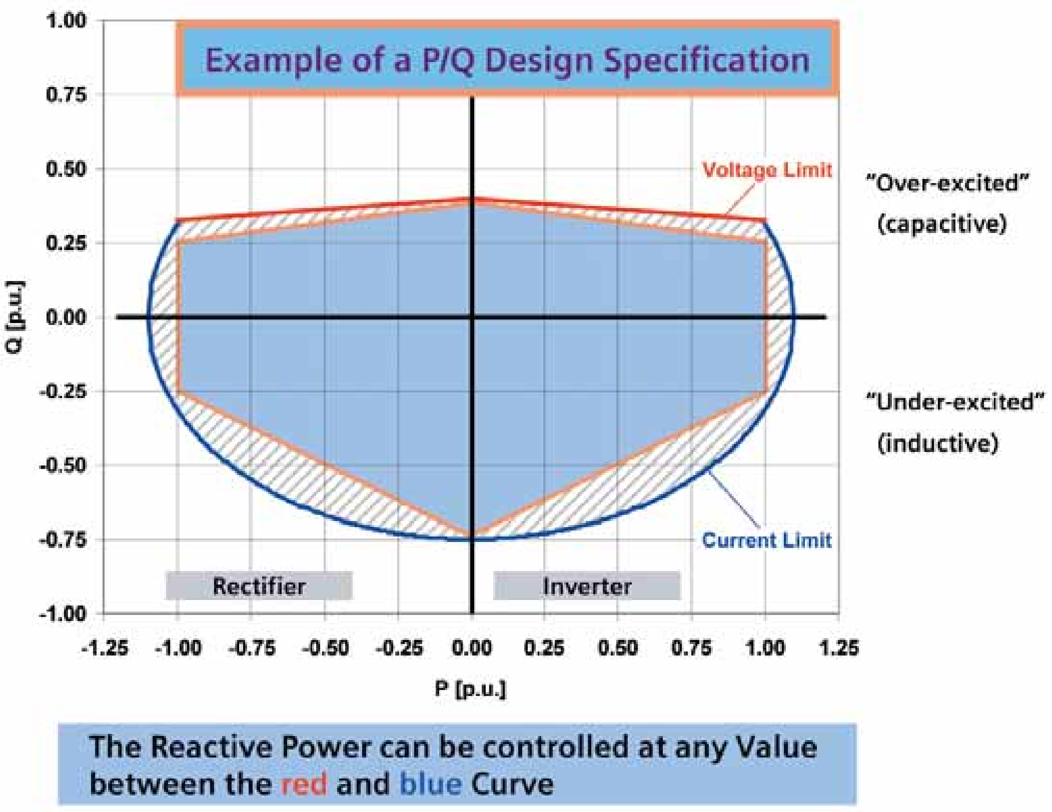
Fig. 3: General Features of VSC Technology



The Reactive Power is defined by both red and blue Curves. It is a Function of Active Power and AC-Voltage

Typically, Reactive Power Consumption of HVDC Classic is $Q = 0.5\ P_d$

Fig. 4: HVDC "Classic" – Generic P/Q Diagram



The Reactive Power can be controlled at any Value between the red and blue Curve

Fig. 5: HVDC PLUS – Typical P/Q Diagram

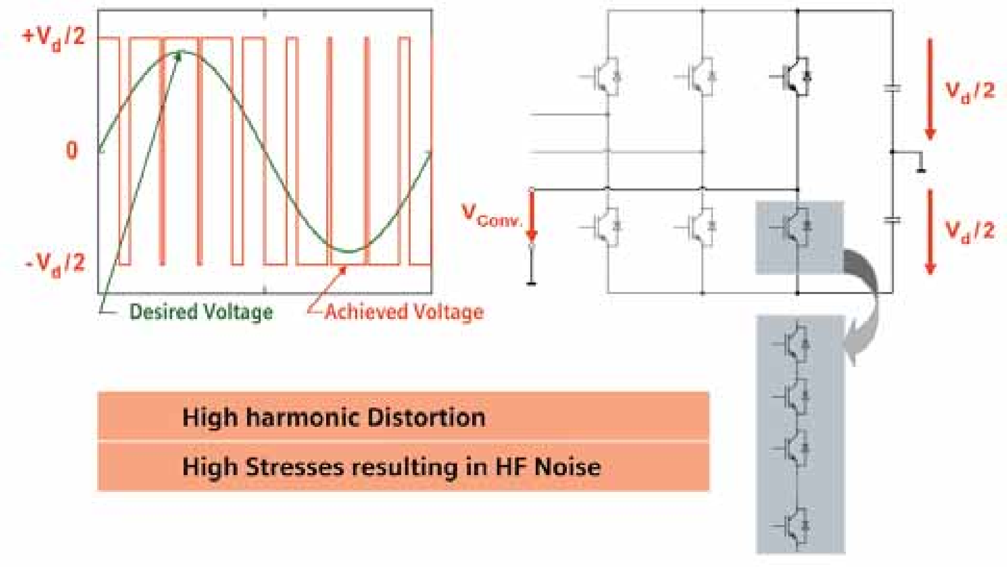


Fig. 6: VSC Technology – a look back

Up to now, the implemented VSC converters for HVDC applications have been based on two or three-level technology which enables switching two or three different voltage levels to the AC terminal of the converter. For such converter topologies a high number of semiconductor devices with blocking capability of a few kilovolts are connected in series – up to several hundreds per converter arm, depending on the DC voltage. To ensure uniform voltage distribution not only statically but also dynamically, all devices connected in series in one converter arm have to switch simultaneously. High and steep voltage steps are applied at the AC converter terminals which causes high component stresses and require extensive filtering measures.

In Fig. 6, the principle of the two-level converter technology is depicted. From the figure, it can be seen that the converter voltage, created by the PWM (Pulse-Width Modulation), is far from the desired "green" voltage. It needs AC filters to achieve an acceptable waveform.

2.2 The Modular Multilevel Converter (MMC) Approach

Both the size of voltage steps and the related voltage gradients can be reduced or minimized if the AC voltage generated by the converter can be selected in smaller increments than at two or three levels only.

The more steps that are used, the smaller is the proportion of harmonics and the lower is the high-frequency noise. Converters with high number of steps are termed multilevel converters.

With a high number of levels the switching frequency of individual semiconductors can be reduced. Since each switching event creates losses in the semiconductors, converter losses can be effectively reduced.

Different multilevel topologies [7–10], such as diode clamped converter or converters with what is termed "flying capacitors" were proposed in the past and have been discussed in many publications.

In Fig. 7, a comparison of two, three and multilevel technology is depicted. A new and different approach is the Modular Multilevel Converter (MMC) technology [9].

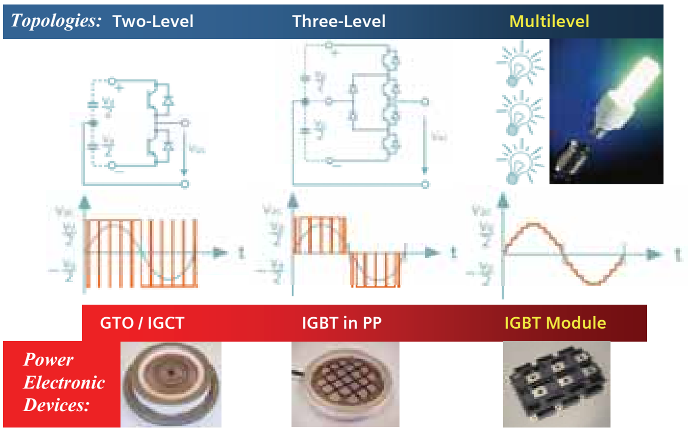
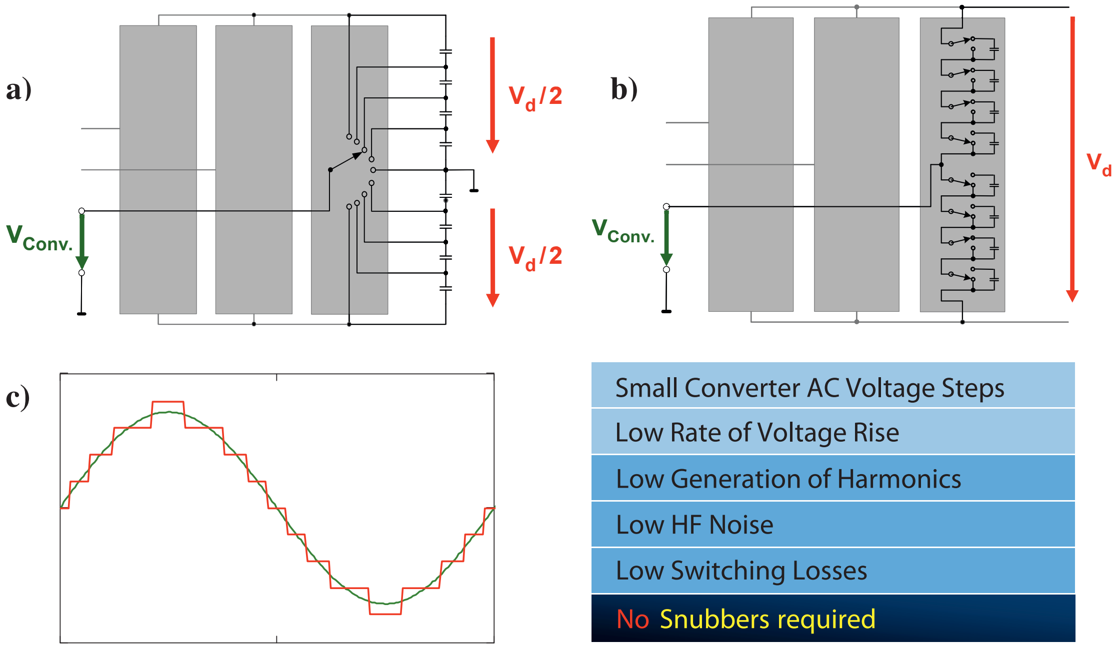


Fig. 7: The Evolution of VSC and HVDC PLUS



Small Converter AC Voltage Steps
Low Rate of Voltage Rise
Low Generation of Harmonics
Low HF Noise
Low Switching Losses
No Snubbers required

Fig. 8: The Multilevel Approach
a) “Basic Idea”
b) The MMC Solution
c) Sinus Approximation – and Benefits

The basic idea of a multilevel converter and the principle design of an MMC are shown in Fig. 8. Fig. 9 depicts the HVDC PLUS MMC solution in detail.

An MMC consists of six converter arms. Each of them comprises a high number of power modules (PM) and one converter reactor connected in series. The power modules contain [9, 16, 17]:

- an IGBT half bridge as a switching element
- a DC capacitor unit for energy storage

For the sake of simplicity, the electronics for the control of the power semiconductors, the monitoring of the capacitor voltage, and the communication with the higher-level controllers are not shown in Fig. 9.

Three different states are relevant for the proper operation of a power module, as illustrated in Table I:

1) “Energization” – Both IGBTs are switched off:

This can be compared with the blocked condition of a two-level converter. Upon charging, i.e. after closing the AC power switch, all power modules of the converter are in this condition. Moreover, in the event of a serious failure all power modules of the converter are put in this state. During normal operation, this condition does not occur. If the current flows from the positive DC pole in the direction of the AC terminal during this state, it charges the capacitor. When it flows in the opposite direction, the freewheeling diode D2 bypasses the capacitor.

2) “Capacitor-On” – IGBT1 is switched on, IGBT2 is switched off:

Irrespective of the current flow direction, the voltage of the storage capacitor is applied to the terminals of the power module. Depending on the direction of flow, the current either flows through D1 and charges the capacitor, or through IGBT1 and thereby discharges the capacitor.

3) “Capacitor-Off” – IGBT1 is switched off, IGBT2 is switched on:

In this case, the current either flows through IGBT2 or D2 depending on its direction which ensures that zero voltage is applied to the terminals of the power module (except for the conducting- state voltage of the semiconductors). The capacitor voltage remains unchanged.

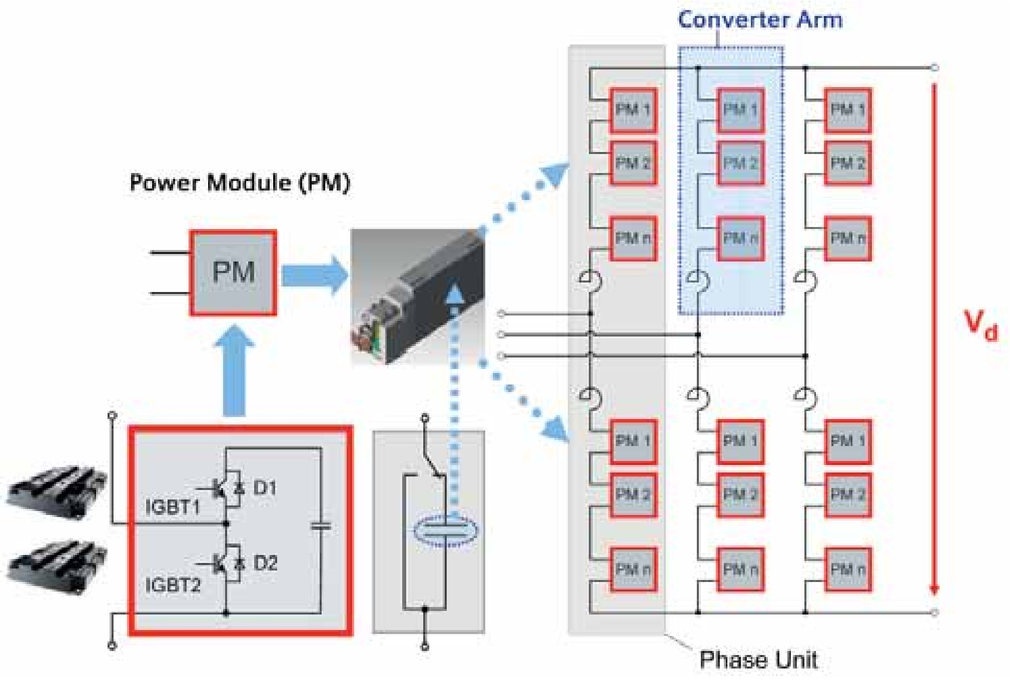
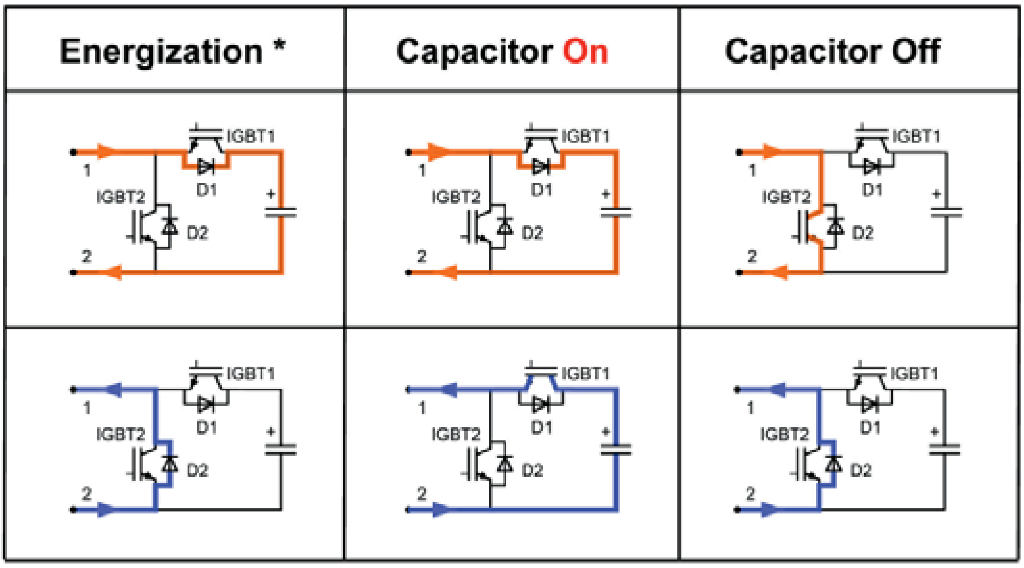


Fig. 9: HVDC PLUS – Basic Scheme



* Converter blocked

Table I: States and Current Paths of a Power Module in the MMC Technology

It is possible to separately and selectively control each of the individual power modules in all phase units. The two converter arms of each phase unit represent a controllable voltage source. The total voltage of the two converter arms in each phase unit equals the DC voltage, and by adjusting the ratio of the converter arm voltages in one phase unit, the desired sinusoidal voltage at the AC terminal is achieved.

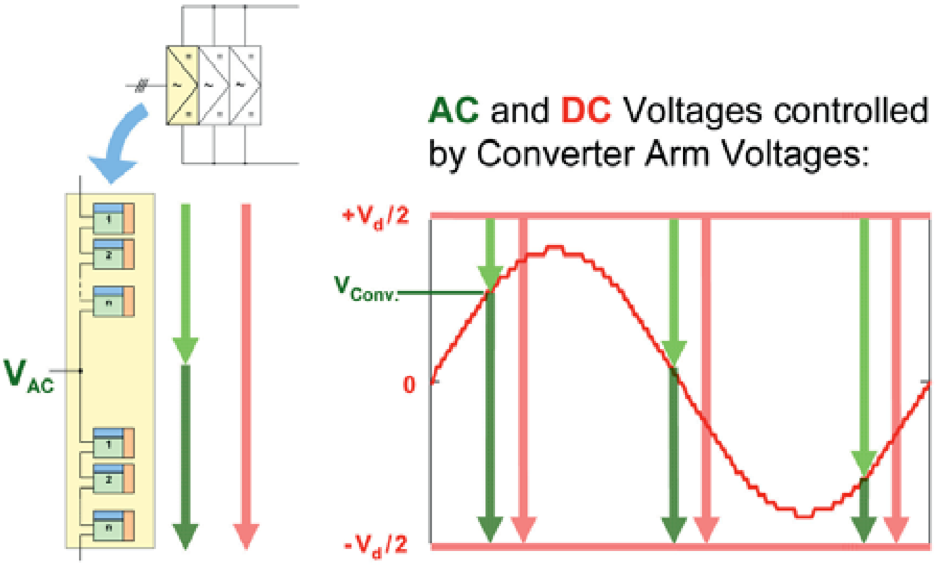


Fig. 10: The Result – MMC, a perfect Voltage Generation

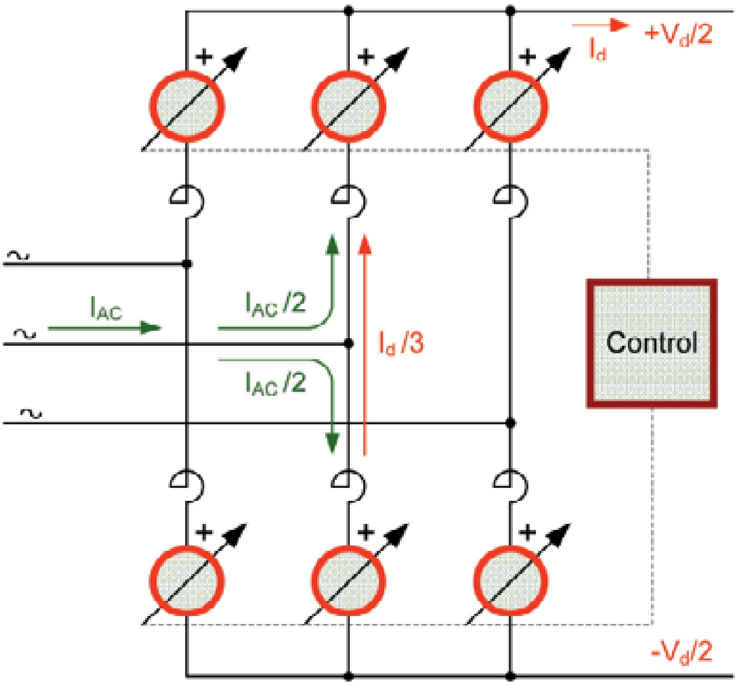


Fig. 11: AC & DC Converter Currents – controlled by MMC Voltage Sources

Figs. 9–11 depict this advanced principle of AC voltage generation with MMC. It can be seen that there is no or – in the worst case – negligible need for AC voltage filtering to achieve a clean voltage.

As is true in all technical systems, the possibility of sporadic failure of individual components cannot be excluded, even with the most meticulous engineering and 100-percent testing. However, if a single component failure occurs, the operation of the system must not be impeded as a result. In the case of an HVDC transmission system this means that there must be no interruption of the energy transfer and that the system will actually continue to operate until the next scheduled shut-down for maintenance.

Redundant power modules are therefore integrated into the converter, and, unlike in previous redundancy concepts, the unit can now be designed so that, upon failure of a power module in a converter arm, the remaining power modules are not subjected to a higher voltage. The inclusion of the redundant power modules thus merely results in an increase in the number of power modules in a converter arm that deliver zero voltage at their output during operation. In the event of a power module failure during operation this fault is detected and the defective power module is shorted out by a highly reliable high-speed bypass switch, ref. to Fig. 12. This provides full functionality, as the current of the failed module can continue to flow, and the converter operates without any interruption.

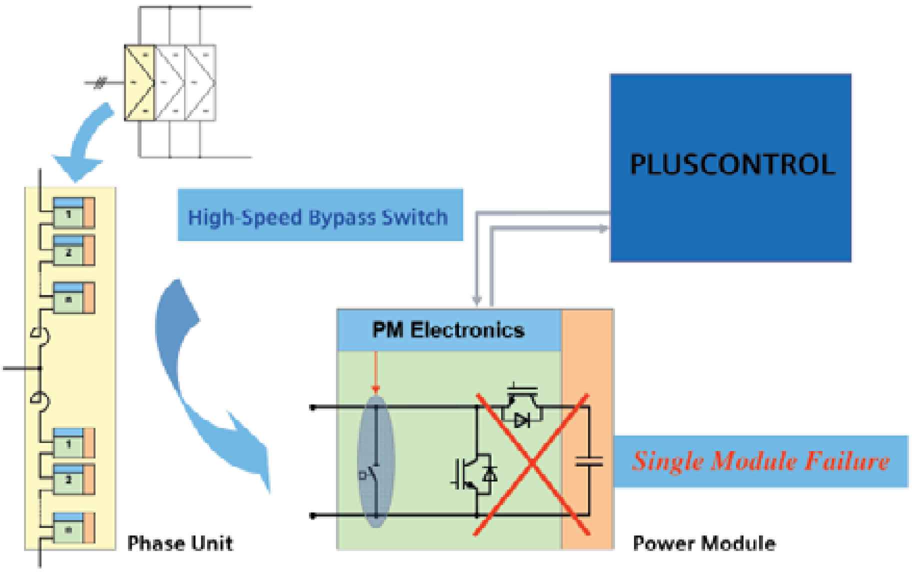


Fig. 12: MMC – Redundant Submodule Design

As in all multilevel topologies it is necessary to ensure, within certain limits, a uniform voltage distribution across the individual capacitors of the multilevel converter. When using the MMC topology for HVDC this is achieved by periodic feedback of the current capacitor voltage to a central control unit. The time intervals between these feedback events are less than 100 microseconds.

Due to the fact that in the converter arms current flows in both directions in each line cycle, and therefore charging and discharging of the individual capacitors is possible. Evaluation of the feedback and selective switching of the individual power modules can be used to balance the power module voltages. With this approach, the capacitor voltages of all power modules of a converter arm in HVDC PLUS are maintained within a defined voltage band.

From the perspective of the DC circuit, the described topology looks like a parallel connection of three voltage sources – the three phase units that generate all desired DC voltages. During steady-state operation, the voltage sources (ref. to Fig. 11) are controlled in order to achieve one third of the total DC current in each phase unit and to achieve an equal sharing of the AC current in the upper and lower part of each phase unit. Each of the 6 variable voltage sources are designed with a number of identical but individually controllable power modules, as shown in Fig. 6. In practice, however, there will be little difference between the momentary values of the three DC voltages, owing to the finite number of available voltage steps.

To reduce the resulting balancing currents between the individual phase units to a very low value by means of appropriate control methods, a converter reactor is required in the individual converter arms. These reactors are also used to substantially reduce the effects of faults arising within or outside the converter station. As a result, unlike in previous VSC topologies, current rise rates of only a few tens of amperes per microsecond are encountered for critical faults.

These faults are swiftly detected, and, due to the relatively low current rise rates, the IGBTs can be turned off at uncritical current levels. This provides effective and reliable protection of the system.

The following describes a very interesting fault occurrence:
In the event of a short-circuit between the DC terminals of the converter or along the transmission route, the current rises in excess of a certain threshold value in the converter arms, and, due to the aforementioned limitation of the speed in the current rise, the IGBTs can be switched off within a few microseconds before the current can reach a critical level, which provides an effective protective function. Thereafter – as with any VSC topology – current flows from the three-phase AC system through the free-wheeling diodes to the short-circuit, so that the only way this fault can be corrected is by opening the AC circuit breaker.

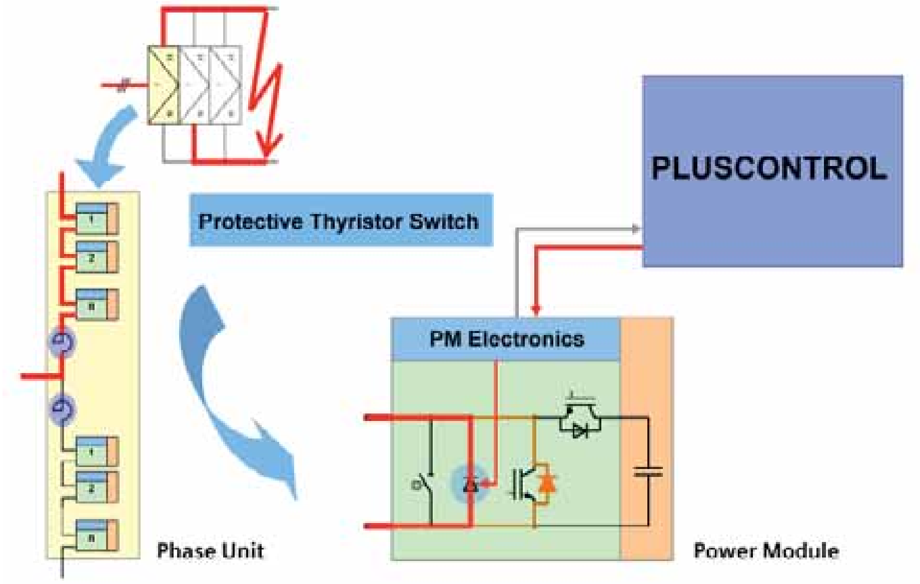


Fig. 13: Fully suitable for DC OHL Application – Example Line-to-Line Fault

The fast recovery free-wheeling diodes used with IGBT modules have a relatively low surge current withstand capability. In an actual event, the diodes have to withstand a fault current without damage until the circuit breaker opens, i.e. in most cases for at least three line cycles. In HVDC PLUS, a protective function at the power module level effectively reduces the load of the diodes until the circuit breaker opens. This protective measure consists of a press-pack thyristor, which is connected in parallel to the endangered diode and is fired in the event of a DC line-to-line fault, ref. to Fig. 13.

As a result, most of the fault current flows through the thyristor and not through the diode it protects. Press-pack thyristors have an inherent capability to withstand high surge currents. This characteristic is also useful in conventional, line-commutated HVDC transmission technology. This fact makes HVDC PLUS suitable even for overhead transmission lines, an application previously reserved entirely for line-commutated converters with thyristors.

Thanks to its modular construction, the HVDC PLUS converter is extremely well scalable, i.e. conveniently adaptable to any required power and voltage ratings. The required number of power modules per converter arm can be realized by a horizontal array of such units and – if required – by assembling them in a vertical arrangement to meet the specific project requirements. Other arrangements are also possible.

Fig. 14 depicts a view of an MMC design. In principle, both a standing and a suspended construction can be readily achieved. However, a standing construction was chosen, since in that case the converter design imposes less special requirements to the converter building.

If required in specific projects, highly effective protective measures against severe seismic loads can also be implemented (ref. to Fig. 14). For such a situation, provisions have been made for diagonal braces at the individual units that ensure adequate stability of the construction.

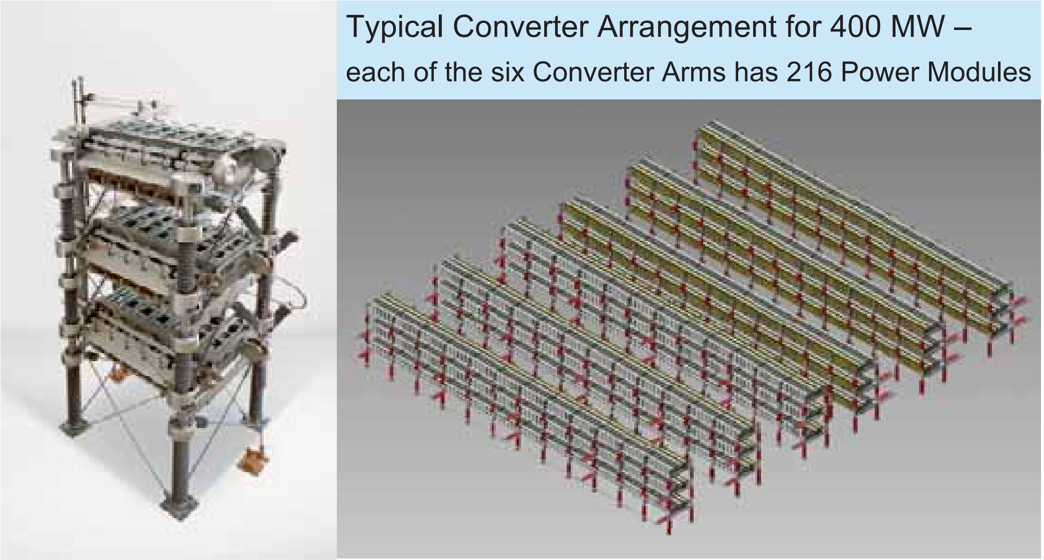


Fig. 14: HVDC PLUS – The Advanced MMC Technology

Each power module is connected via two optical fibers to the PLUSCONTROL (Fig. 15), the central control unit. The PLUSCONTROL was developed specifically for HVDC PLUS and has the following functions:

- Calculation of appropriate converter arm voltages at time intervals of several microseconds
- Selective control of the power modules depending on the direction of power flow and on the relevant capacitor voltages in the power modules so as to assure reliable balancing of capacitor voltages

In addition to the current status of each power module, the momentary voltage of the capacitor is communicated via the fiber optics to the PLUSCONTROL. Control signals to the power module, such as the signals for the switching of the IGBTs, are communicated in the opposite direction from the PLUSCONTROL to the power modules.

Key features of the PLUSCONTROL are:

- Mechanical construction in standard 19-inch racks,
- High modularity and scalability through plug-in modules, and the capability of integrating different numbers of racks into the system,
- Uniform redundancy concept with an active and passive system and the ability to change over on the fly,
- Modules and fans can be replaced during operation,
- Sufficient interfaces for communication and control of well over 100 power modules per rack, and
- High performance with respect to computational power and logic functions.

The PLUSCONTROL is fully integrated into the industry-proven SIMATIC TDC environment, which provides the platform for the measuring system and the higher-level control and protection.

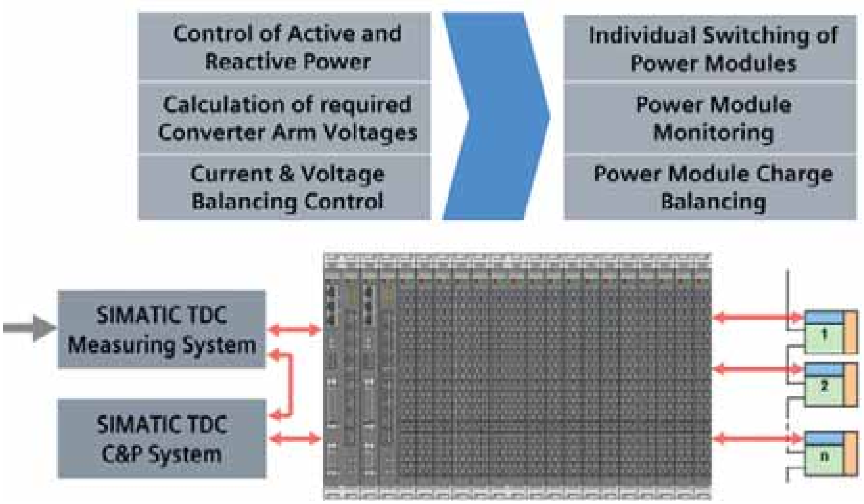


Fig. 15: Main Tasks of PLUSCONTROL

The MMC topology used in HVDC PLUS differs from other, already familiar VSC topologies in design, mode of operation, and protection capabilities. The following summarizes the essential differences and related advantages:

- A highly modular construction both in the power section and in control and protection has been chosen. As a result, the system has excellent scalability and the overall design can be engineered in a flexible way. Thus, the converter station can be perfectly adapted to the local requirements, and depending on those requirements, the design can favor either a converter hall with a small footprint or a building with a low profile.
- In normal operation, no more than one level per converter arm switches at any given time. As a result, the AC voltages can be adjusted in very fine increments and a DC voltage with very little ripple can be achieved, which minimizes the level of generated harmonics and in most cases completely eliminates the need for AC filters. What's more, the small voltage steps that do occur cause very little radiant or conducted high-frequency interference.
- The low switching frequency of the individual semiconductors results in very low switching losses. Total system losses are therefore relatively low for VSC PLUS technology, and the efficiency is consequently higher in comparison with existing two and three-level solutions.
- HVDC PLUS utilizes industrially proven standard components, such as IGBT modules, which are robust and highly reliable. These components have proven their reliability and performance under severe environmental and operating conditions in other applications, such as traction drives. This wide range of applications results in long-term availability and continuing development of these standard components.
- The encountered voltage and current loads support the use of standard AC transformers.
- The achievable power range as well as the achievable DC voltage of the converter is determined essentially only by the performance of the controls, i.e. the number of power modules that can be operated. With the current design, transmission rates of 1000 MW and above can be achieved.
- Due to the elimination of additional components such as AC filters and their switchgear, high reliability and availability can be achieved. What's more, the elimination of components and the modular design can shorten project execution times, all the way from project development to commissioning.
- With respect to later provision of spare-parts, it is easy to replace existing components by state-of-the-art ones, since the switching characteristics of each power module are determined independently of the behavior of the other power modules. This is an important difference to the direct series-connection of semiconductors as in the two-level technology where nearly identical switching characteristics of the individual semiconductors are mandatory.
- Internal and external faults, such as short-circuit between the two DC poles of the transmission line, are reliably managed by the system, due to the robust design and the fast response of the protection functions.

Figs. 16–18 summarize the advantages in a comprehensive way. Added to these are the aforementioned advantages that ensue from the use of VSC technology in general (see Fig. 3).

With these features, HVDC PLUS is ideally suitable for the following DC systems (Fig. 18):

- Cable transmission systems. Here, the use of modern extruded cables, i.e. XLPE, is possible, since the voltage polarity in the cable remains the same irrespective of the direction of current flow.
- Overhead transmission lines, due to the capability to withstand DC side short-circuits
- Back-to-Back arrangement, i.e. rectifier and inverter in one station
- The implementation of multiterminal systems is relatively simple with HVDC PLUS. In these systems, more than two converter stations are linked to a DC connection.
- The converters can to some extent be used as STATCOMs, e.g. when the transmission line or cable is out of service during maintenance or faults. STATCOM with PLUS technology is also useful in unbalanced AC networks, for instance in the presence of large single-phase loads. Symmetry of the three-phase system can be improved by using load unbalance control.

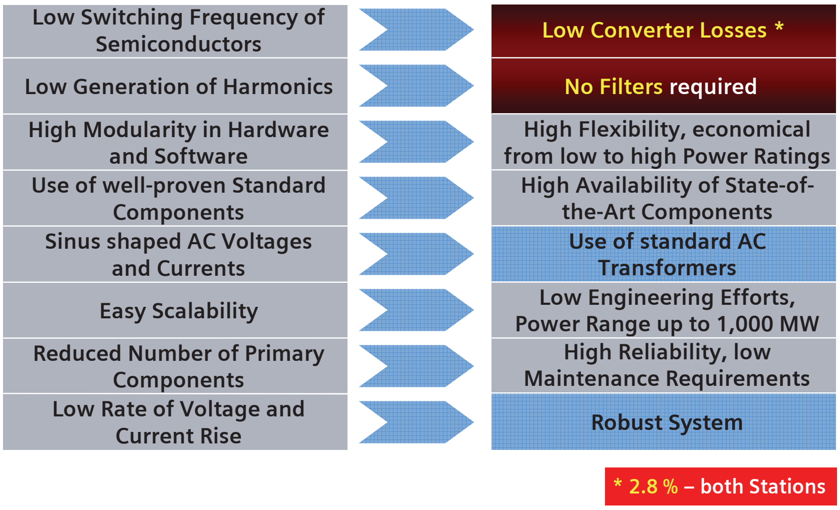
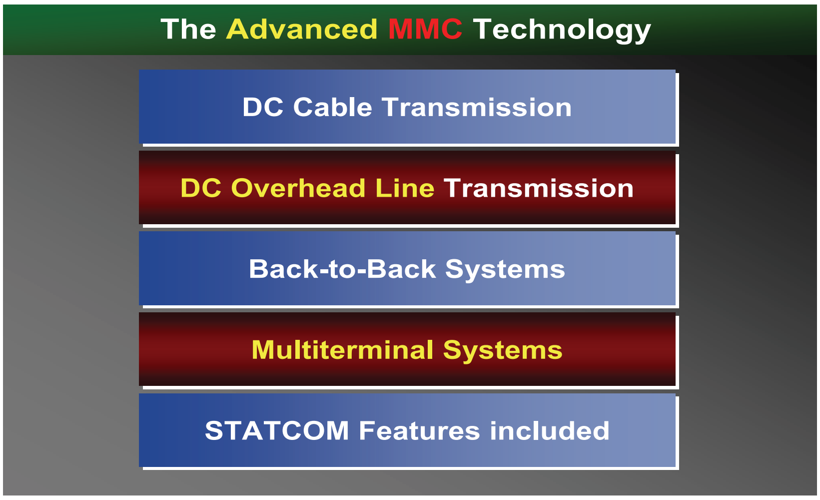


Fig. 16: Features and Benefits of MMC Topology

This multitude of possibilities in combination with the performance of HVDC PLUS opens up a wide range of applications for this technology:

- DC connections for a power range of up to 1,000 megawatt, in which presently only line-commutated converters are used,
- Grid access to very weak grids or islanded networks, and
- Grid access of renewable energy sources, such as offshore wind farms, via HVDC PLUS. This can substantially help reduce CO_2 emissions. And vice versa, oil platforms can be supplied from the coast via HVDC PLUS, so that gas turbines or other local power generation on the platform can be avoided.

Furthermore, with its technical performance (Figs. 16, 17) and its space-saving design (Fig. 18) HVDC PLUS is tomorrow's solution for the supply of megacities.



The Advanced MMC Technology

DC Cable Transmission

DC Overhead Line Transmission

Back-to-Back Systems

Multiterminal Systems

STATCOM Features included

Fig. 17: Applications and Features of HVDC PLUS

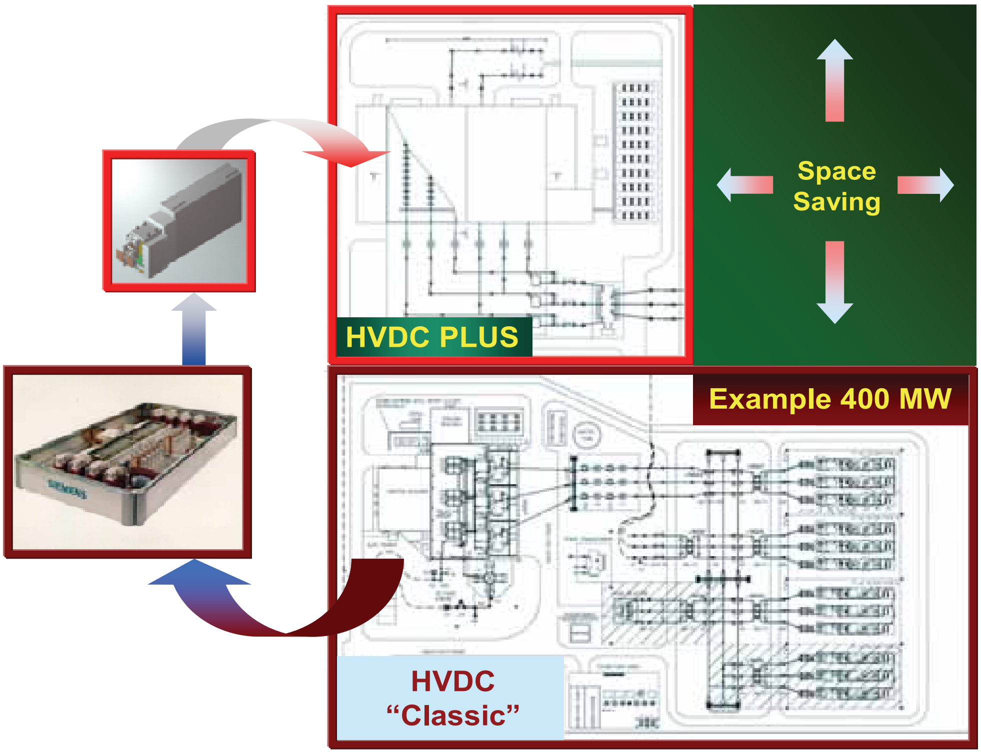


Fig. 18: Space Saving in Comparison with HVDC "Classic"

2.3 The Trans Bay Cable HVDC Project

Due to the aforementioned technical and economical benefits, in September 2007, Siemens secured an order to supply two converter stations for a new submarine HVDC transmission link in the Bay of San Francisco. The HVDC PLUS system will transmit up to 400 megawatts at a DC voltage of ± 200 kV. This is the first order for the innovative HVDC PLUS technology. A project overview is given in Fig. 19.

From March, 2010, the 55 mile (88 kilometers) long HVDC PLUS system will transmit electric power from the converter station in Pittsburg to the converter station in San Francisco, providing a dedicated connection between the East Bay and San Francisco. Main advantages of the new HVDC PLUS link are improved network security and reliability due to grid enhancement, voltage support and reduction in system losses.

Today, the major electric supply for the City of San Francisco is coming from the south side of the San Francisco peninsula. The city relies mainly on AC grids which run along the lower part of the bay. With the new HVDC PLUS interconnection link, power flows directly into the center of San Francisco and closes the loop of the already existing “Greater Bay Area” transmission. This will increase the system security. The DC cables will be buried in a safe corridor separate from any existing AC cables.

Due to the DC transmission link, the building of additional new power plants in the City of San Francisco may be postponed or even avoided.

The link will reduce grid congestion in the East Bay and it will also boost the overall security and reliability of the power system.

The order was placed by Trans Bay Cable LLC, based in San Francisco, and a wholly-owned subsidiary of the project developer Babcock & Brown.

As the consortium leader, Siemens was awarded a turnkey contract which comprises the converter stations for the HVDC PLUS system, including engineering, design, manufacturing, installation and commissioning of the HVDC transmission system. The design fulfills all requirements which have to be considered for the electrical components as well as for all buildings in a highly seismic active zone such as San Francisco.

The consortium partner Prysmian will supply and install the submarine cables.

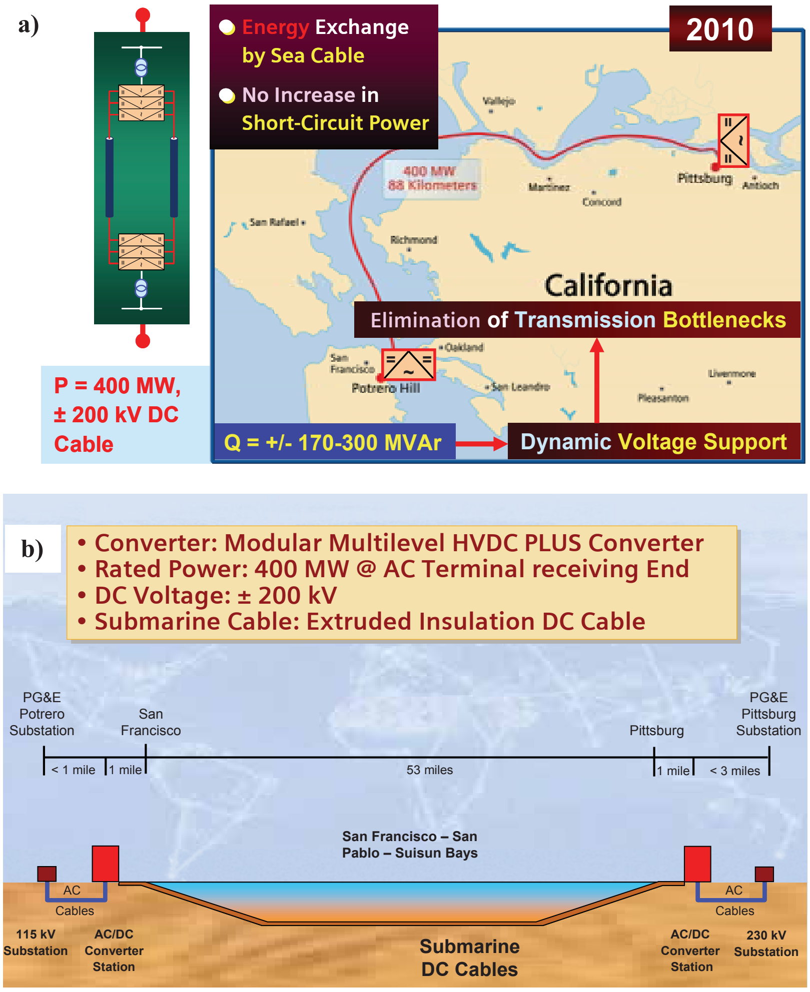


Fig. 19: Trans Bay Cable, USA – World’s 1st VSC HVDC Project with Advanced MMC-Technology and ± 200 kV XLPE DC Cable
a) Geographic Map and System Requirements
b) Siemens Converter Stations and Prysmian Cable Technologies

The new link provides tremendous benefits for power transmission. It will help increase sustainability and security of transmission systems significantly.

As an example, a significant reduction in transmission constraints by using HVDC PLUS for the Trans Bay Cable Project is depicted in Fig. 20.

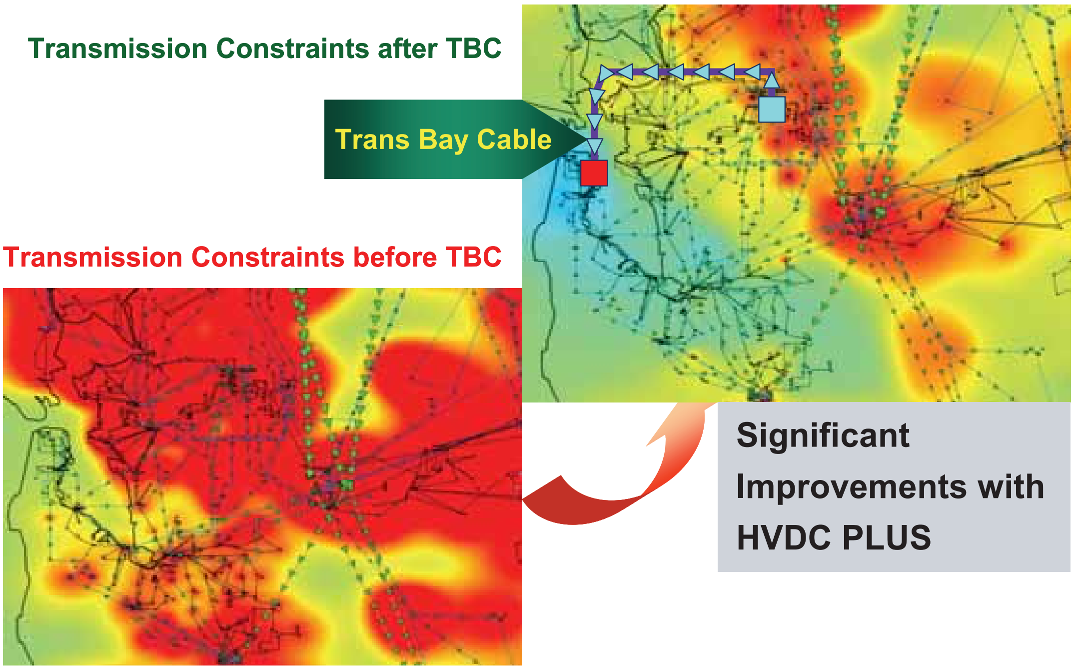


Fig. 20: Benefits of HVDC PLUS for Trans Bay Cable Project

3. Design Verification

Numerous activities are carried out to ensure that the Transbay Cable transmission system will perform as required.

3.1 Equipment Tests

The test schedule includes routine tests and type tests for all major equipment. Fig. 21 shows the dielectric type test of a section of a converter arm.

3.2 System Performance Verification

The verification process for the system performance of the converter and its controls includes extensive computer simulations as well as a wide range of tests with the real control and protection equipment connected to digital and analog simulator hardware.

For further verification of the performance of the controls and also the simulator models a full scale converter hardware in the form of a 30 MW Back-to-Back converter was installed.

Fig. 22 shows details of this test facility.

Fig. 21: Dielectric Type Test of HVDC PLUS

Fig. 22: 30 MW Hardware Functional Tests

3.3 Results of Computer Simulations

Fig. 23 depicts the results of a computer simulation for the 400 MW MMC system which will be applied in the case of the Trans Bay Cable project. The figure clearly shows that with 200 power modules per converter arm no additional AC filtering will be required.

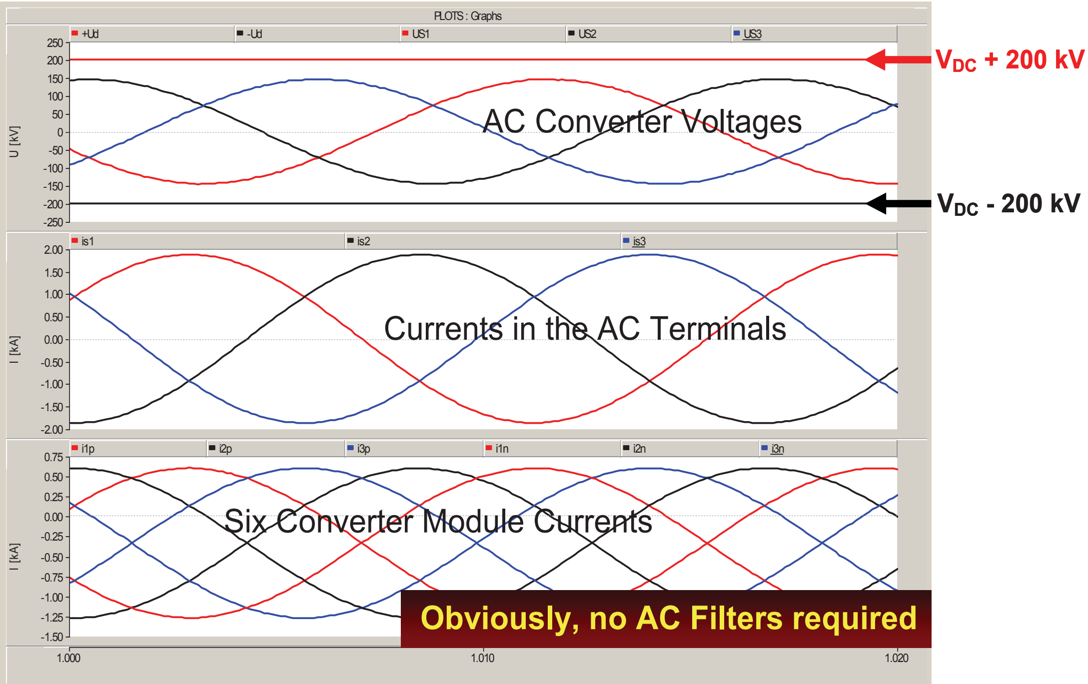


Fig. 23: 400 MW with 200 Power Modules per Converter Arm

Figs. 24–25 show the transient performance of HVDC PLUS during AC faults, incl. “fault ride-through capability”.

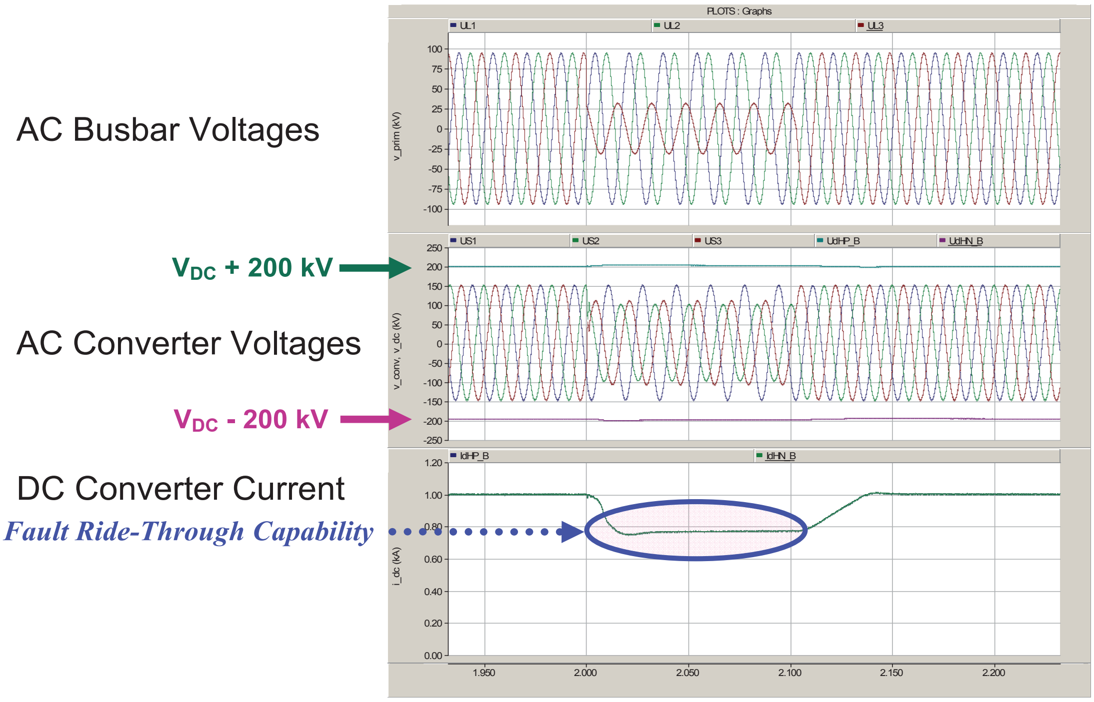


Fig. 24: Dynamic Response to an AC Line-to-Ground Remote Fault on the Inverter Side

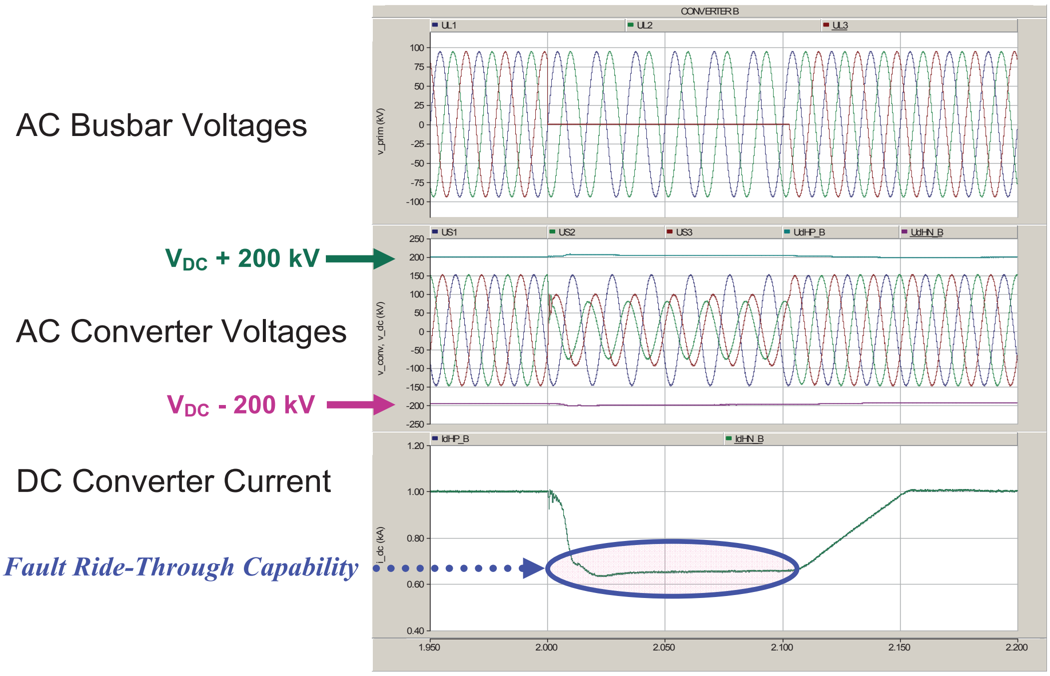


Fig. 25: Dynamic Response to an AC Line-to-Ground Busbar Fault on the Inverter Side

4. Example of Station Layouts

In Fig. 18 the space saving of HVDC PLUS in comparison with HVDC "Classic" is illustrated.

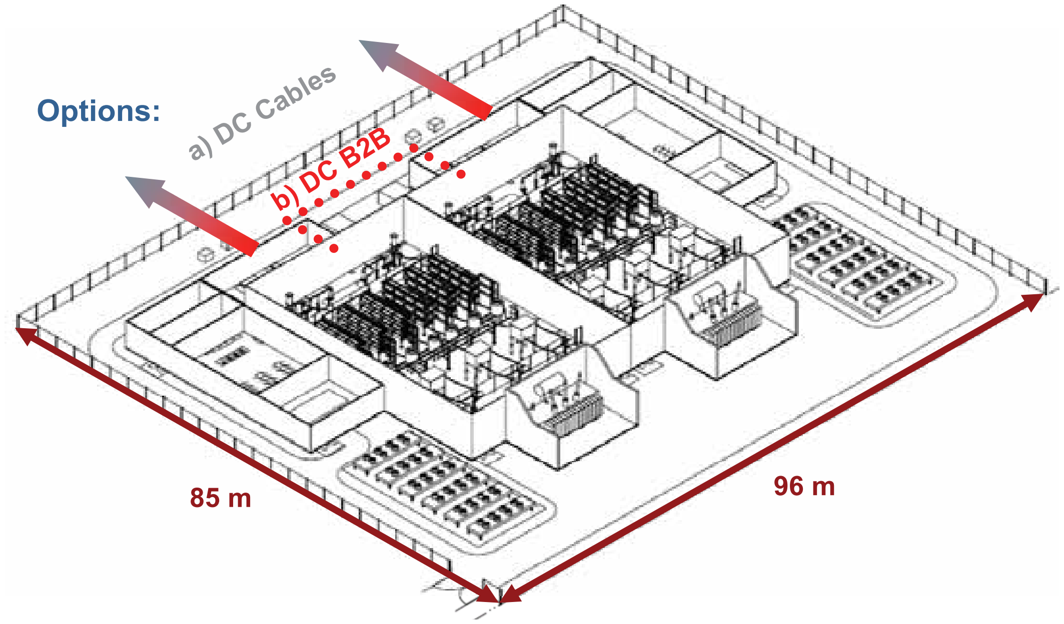
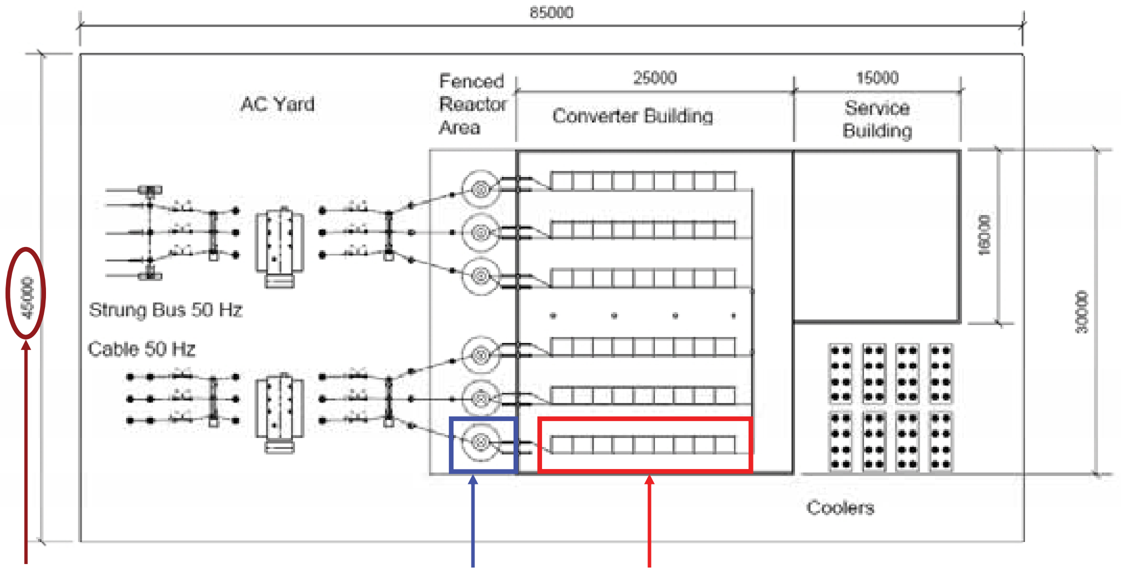


Fig. 26: Example of HVDC PLUS Station – 2 x 100 MW

In principle, there are two configuration possibilities. Fig. 26 depicts a fully horizontal arrangement which can be used either as a 200 MW converter station for long-distance transmission cable/overhead line, or as a 100 MW B2B. In Fig. 27, the 100 MW B2B option has a vertical arrangement of reactors and converters, thus saving approx. 50 per cent of space.



Half the Width by vertical Arrangement: 2 Reactors and 2 Converter Modules on Top of each other

Fig. 27: HVDC PLUS Station – Option for 100 MW B2B

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