0. Introduction

Deregulation and privatization is posing new challenges on high voltage transmission systems. System elements are going to be loaded up to their thermal limits, and power trading with fast varying load patterns will contribute to an increasing congestion. In this respect, interconnection of separated power systems may offer important technical, economical and environmental advantages. In the future of liberalised power markets, these advantages will become even more important: pooling of large power generation stations, sharing of spinning reserve and use of most economic energy resources, taking into account also ecological constraints: nuclear power stations at special locations, hydro energy from remote areas, solar energy from desert areas and connection of large off-shore wind farms.

For the interconnections, innovative solutions to avoid congestion and to improve stability will be essential. HVDC (High Voltage Direct Current) provides the necessary features to avoid technical problems in the power systems, and it increases the transmission capacity and system stability very efficiently and it assists in prevention of cascading disturbances. HVDC can also be applied as a hybrid AC-DC solution in synchronous AC systems either as Back-to-Back for grid power flow control (elimination of congestion and loop flows) or as long-distance point-to-point transmission. HVDC transmission has developed to a mature technique with high power ratings. There are now ways of transmitting 3 - 4 GW over large distances with only one bipolar DC transmission system. For some countries, UHV solutions with AC voltages of 1000 kV and DC systems with 800 kV are in the planning stage. This will increase the transmission capacity for AC links up to 10 GW and for DC systems up to 5 - 6 GW.

As a consequence of “lessons learned” from the large Blackouts in 2003, HVDC and hybrid AC-DC solutions will play an important role for the system developments, leading to “Smart Grids” with better controllability of the power flows.

Benefits of DC and hybrid solutions for system enhancement and grid interconnection are demonstrated and DC UHV technology issues are discussed. HVDC projects are presented, including parallel operation of HVDC and FACTS (Flexible AC Transmission Systems).
1. Development of Transmission Systems

The development of power systems follows the requirements to transmit power from generation to the consumers. With an increased demand for energy and the construction of new generation plants, first built close and then at remote locations from the load centers, the size and complexity of power systems have grown. Examples of large interconnected systems are the Western and Eastern European systems UCTE (installed capacity 530 GW) and IPS/UPS (315 GW), which are planned to be interconnected in the future.

With an increasing size of the interconnected systems, the technical and economical advantages diminish. This is related to problems regarding load flow, power oscillations and voltage quality. If power is to be transmitted through the interconnected system over longer distances, transmission needs to be supported. This is, for example, the case in the UCTE system, where the 400 kV voltage level is in fact too low for large cross-border and inter-area power exchange. Bottlenecks are already identified, and for an increase of power transfer, advanced solutions need to be applied.

Large blackouts in America and Europe confirmed clearly, that the favorable close electrical coupling might also include risk of uncontrollable cascading effects in large and heavily loaded interconnected systems. Additional problems are expected when renewable energies, such as large wind farms, have to be integrated into the system, especially when the connecting AC links are weak and when there is no sufficient reserve capacity in the neighboring system available. In the future, an increasing part of the installed capacity will, however, be connected to the distribution levels (dispersed generation), which poses additional challenges on planning and safe operation of the systems. In such cases, HVDC and FACTS can clearly strengthen the power systems and improve their performance.

![Diagram](image)

**Fig. 1: Large Power System Interconnections - Benefits of Hybrid Solutions**

Based on the global experience with large blackouts, strategies for the development of large power systems go clearly in the direction of hybrid transmissions, consisting of DC and AC interconnections, including FACTS. Such hybrid interconnected systems offer significant advantages, both technical and in terms of reliability. Fig. 1 shows schematically such a hybrid system using HVDC and FACTS. Power exchange in the neighboring areas of interconnected
systems offering most advantages can be achieved by AC links, preferably including FACTS for increased transmission capacity and for stability reasons. The transmission of large power blocks over long distances should, however, be utilized by the HVDC transmissions directly to the locations of power demand. HVDC can be implemented as direct coupler – the “Back-to-Back” solution (B2B) - or as point-to-point long distance transmission via DC line. The HVDC links can strengthen the AC interconnections at the same time, in order to avoid possible dynamic problems which exist in such huge interconnections.

Fig. 2 depicts how these ideas of hybrid interconnections are reflected in China's grid development.

**Fig. 2: Perspectives of Grid Developments in China - AC & DC Bulk Power Transmission from West to East via three main Corridors**

Focus is on interconnection of 7 large inter-provincial grids of the Northern, Central and Southern systems via three bulk power corridors which will built up a redundant “backbone” for the whole grid. Each corridor is planned for a sum of about 20 GW transmission capacity which shall be realized with both AC and DC transmission lines with ratings of 4 - 10 GW each (at +/- 800 kV DC and 1000 kV AC, ref. to the figure). Therefore, each corridor will have a set-up with 2 - 3 systems for redundancy reasons. With these ideas, China envisages a total amount of about 900 GW installed generation capacity by 2020. For comparison, UCTE and IPS/UPS together sum up to 850 GW today.

The benefits of such a large hybrid power system interconnection are clear:

- Increase of transmission distance and reduction of losses - using UHV
- HVDC serves as stability booster and firewall against large blackouts
- Use of the most economical energy resources - far from load centers
- Sharing of loads and reserve capacity
- Renewable energy sources, e.g. large wind farms and solar fields can much more easily be integrated
However, using the 1000 kV AC lines, there will be in fact stability constraints: if for example such an AC line - with up to 10 GW transmission capacity - is lost during faults, large inter-area oscillations might occur. For this reason, additional large FACTS controllers on the AC lines for stability support are in discussion.

2. Developments in the Field of HVDC

In the second half of last century, high power HVDC transmission technology has been introduced, offering new dimensions for long distance transmission. This development started with the transmission of power in an order of magnitude of a few hundred MW and was continuously increased to transmission ratings up to 3 GW over long distances by just one bipolar line. Transmission distances over 1,000 to 2,000 km or even more are possible with overhead lines. Transmission power of up to 600 - 800 MW over distances of about 300 km has already been implemented using submarine cables, and cable transmission lengths of up to about 1,300 km are in the planning stage.

By these developments, HVDC became a mature and reliable technology. Up to now, almost 55 GW HVDC transmission capacities have been installed worldwide, ref. to Fig. 3. It can be seen that China alone will be contributing significantly to this development because of its rapidly growing economy (GDP) every year.

![Worldwide installed HVDC Capacity: 55 GW in 2005](image)

This is 1.4 % of the Worldwide installed Generation Capacity

An additional 48 GW are expected from China alone until 2020!

Sources: IEEE T&D Committee 2000 - Cigre WG B4-04 2003

**Fig. 3: Worldwide installed Capacity of HVDC Links**

During the development of HVDC, different kinds of applications were carried out. They are shown schematically in Fig. 4. First commercial applications were HVDC sea cable transmissions, because AC cable transmission over more than 60-80 km is technically not feasible due to reactive power limitations. Then, long distance HVDC transmissions with overhead lines were built because they were more economical than transmission with AC lines.
To interconnect systems operating at different frequencies, Back-to-Back (B2B) schemes were applied. B2B converters can also be connected to long AC lines (Fig. 4a).

A further and for the future very important application of HVDC transmission is its integration into the complex interconnected AC system. Fig. 4c depicts this idea for both B2B – as Grid Power Flow Controller (GPFC) - and for long-distance point-to-point transmission. The reasons for these hybrid solutions are basically lower transmission costs as well as the possibility of bypassing heavily loaded AC systems.

Typical configurations of HVDC are depicted in Fig. 5. In Fig. 6, an overview of both standard and extended operating ranges of HVDC is given. While using the full control range of HVDC up to 90°, the B2B can “feature” FACTS functions, e.g. fast voltage control, in the same way as an SVC. As indicated in the figure, this new idea of GPFC as a “FACTS B2B” has been successfully applied in a project at Lamar substation, USA.

The major benefit of the HVDC (in comparison with FACTS), both B2B/GPFC and LDT, is its incorporated ability for fault-current blocking, which serves as an automatic firewall for Blackout prevention in case of cascading events, which is not possible with FACTS.

HVDCPLUS (see Fig. 7) is the preferred technology for interconnection of islanded grids to the power system, such as off-shore wind farms. This technology provides the so-called “Black-Start” feature using self-commutated voltage-sourced converters (VSC). Voltage-sourced converters do not have the need for a “driving” system voltage; they can build up a 3-phase AC voltage via the DC voltage at the cable end, supplied from the converter at the main grid.

In Fig. 8, the benefits of using power electronics for system enhancement are summarized and a comparison of switching frequencies of line-commutated thyristor devices and self-commutated VSC are depicted. Conventional equipment (e.g. breakers, tap-changer transformers) offer very low losses, but the switching speed is too low. Power electronics can provide high switching frequencies up to several kHz, however, with an increase in losses.
**b) HVDC - High Voltage DC Transmission: It forces P to flow**

- Standard with **Thyristors** (Line-Commutated Converter)
- **AC/DC** and **DC/AC** Conversion by **Power Electronics**
- **HVDCPLUS** (Voltage-Sourced Converter - VSC)
- HVDC can be combined with **FACTS**
- **V-Control** included
From Fig. 8, it can be seen that – due to less converter losses – the preferred solution for Bulk Power Transmission is in fact the line-commutated thyristor technology. The today’s losses of high power voltage-sourced converters with high switching frequencies are within the range of 4 - 5 %, which is too much for large bulk power DC transmission projects.
3. UHV Solutions for Bulk Power Transmission

Bulk Power UHV AC and DC transmission schemes over distances of more than 2000 km are currently under planning for connection of various large hydropower stations in China, ref. to section 1. Ultra high DC voltage (up to 800 kV) and ultra high AC (1000 kV) are the preferred voltage levels for these applications, to keep the transmission losses as low as possible.

In India, there are similar prospects for UHV DC as in China, due to the large extension of the grid. AC, they will, however, realize with EHV levels up to 800 kV.

Specific issues for the necessary UHV technology developments are depicted in the following, as seen from the Siemens perspective. It is obvious that the UHV insulation requirements will lead to a huge increase of the mechanical dimensions of all equipment, including PTs, CTs, breakers, disconnectors, busbars, transformers and reactive power equipment. Some main equipment does not require detailed investigations since existing technology basically enables to extrapolate from lower voltage applications. An example for this type of equipment is the DC thyristor valve which is based on a modular design. Additional thyristor levels to be connected in series are well feasible and do not require any conceptual changes. However, for other equipment it has to be verified to which extent existing technology and know-how are adequate for design and manufacturing process. This includes the following equipment:

- AC grid transformers and DC converter transformers including bushings
- AC and DC wall bushings
- DC smoothing reactors
- AC reactive power equipment, including FACTS
- AC breakers and disconnectors
- DC bypass switches and DC disconnectors
- AC and DC measurements

Regarding shunt-connected FACTS controllers, there are no specific additional efforts necessary for the medium voltage equipment at the secondary side of the grid transformers. For series
connected FACTS, if applied, efforts will be needed for a robust construction of the platforms matching the required seismic performance.

Converter transformers are one of the very important components for UHV DC application. It is quite understood that the existing technology and know-how of converter transformers can manage higher DC voltages. Yet, there are critical areas which need careful consideration and further development in order to keep the electrical stresses at a safe level. Above all the windings and the transformer internal part of bushings on the valve side of the converter transformers with the barrier systems and cleats and leads require very careful attention.

In the following, design aspects for key UHV DC equipment are outlined. From Figs. 9-10 it can be seen that for transformers the bushings will be a major issue with regard to mechanical dimensions, including transportation to site.

- **Existing Technology and Know-How can well manage higher DC Voltage Stresses**
- **Transformers for 800 kV HVDC System are within existing Manufacturing Capabilities**
- **Transportation Limits and Converter Configuration will determine Type and Size**
- **R&D in Progress in specific Fields**

![Fig. 9: Transformer for UHV DC – In the State of Development](image)

An example of the complete HVDC station layout is given in Fig. 11. Main idea of this concept is to use two 12-pulse converters with 400 kV DC operating voltage each and then to connect them in series in order to achieve the desired 800 kV arrangement.

A major benefit of this solution, as shown in Fig. 11, will be a smaller size of the converter transformers, if transportation restrictions exist. Furthermore, it increases the redundancy of the transmission: each of the 4 converters of plus and minus pole can be bypassed and the assigned DC line will be operated at 400 kV reduced voltage level.

Due to this, the single line diagram of +/- 800kV UHV DC converter station will be mostly the same as a +/- 500kV HVDC converter station. A configuration of two 12 pulse-groups per pole has also a long term operation experience worldwide. It means there is no basic new concept to be developed.

The arrangement of the valve-units in two 400 kV valve halls per pole is outlined in Fig. 12.

Main benefit will be the use of proven modular technologies by just expanding them to the new application.

This is also valid for the AC and DC control and protection schemes. However, the measurements will need to be adapted to the higher voltage level.
Fig. 10: UHV DC Bushing at Test Lab TU Graz – Austria

Fig. 11: Fully redundant HVDC Scheme – with two 400 kV 12-Pulse Converters per Pole
The 800 kV DC concept can be summarized as follows:

- **UHV DC Valves using proven modular Design based on existing Technology and Know-How for DC Voltage 800 kV**
- **Valve Tower Configuration: Double or Quadruple Valve**
- **Proven existing LTT Technology**

Based on the discussions and descriptions, following conclusion can be made for the design of UHV AC and DC bulk power transmission systems:

- From the main equipment point of view UHV DC systems of up to 800 kV and UHV AC systems of up to 1000 kV are technically feasible
- In general, UHV equipment can be designed and manufactured on the basis of existing technologies
- For most of the station equipment only some or even no R&D is anticipated

4. Grid Enhancement and System Interconnection with HVDC
4.1 Gui-Guang HVDC Project – China

The 3000 MW +/-500kV bipolar Gui-Guang HVDC system (Fig. 13) with a transmission distance of 980 km was build to increase the transmission capacity from west to east. It is integrated into the
large AC interconnected system. In the same system there is also an already existing HVDC scheme in operation. Both DC systems operate in parallel with AC transmission in this grid. In addition to that, Fixed Series Compensation (FSC) and Thyristor Controlled Series Compensation (TCSC) are used in the system. Due to long transmission distances, the system experiences severe power oscillations after faults, close to the stability limits. With its ability to damp power oscillations, the HVDC Gui-Guang essentially contributes to reliable operation of the system.

4.2 HVDC Project Neptune – USA

After the 2003 blackout in the United States, new projects are smoothly coming up in order to enhance the system security.

One example is the Neptune HVDC project. Siemens PTD has been awarded a contract by Neptune Regional Transmission System LLC (RTS) in Fairfield, Connecticut, to construct an HVDC transmission link between Sayreville, New Jersey and Long Island, New York. Because new overhead lines can not be built in this high density populated area, power should directly be brought to Long Island by HVDC cable transmission, by-passing the AC sub-transmission network. Neptune RTS was established to develop and commercially operate power supply projects in the United States. By delivering a complete package of supply, installation, service and operation from one single source, Siemens is providing seamless coverage of the customer’s needs. The availability of this combined expertise fulfills the prerequisites for financing these kinds of complex supply projects through the free investment market.

Siemens and Neptune RTS developed the project over three years to prepare it for implementation. In addition to providing technological expertise, studies, and engineering services, Siemens also supported its customer in the project’s approval process.

Fig.13: Geographic Location and main Data of Gui-Guang HVDC Project - China
In Fig. 14, highlights of this innovative project that are typical for future integration of HVDC into a complex synchronous AC system are depicted.

4.3 East-South Interconnector – India

The grid in India has been developed to regional power systems which were operating asynchronously. Later interconnections between regional systems were made by AC and by Back-to-Back HVDC. The first HVDC long distance transmission was Rihand-Delhi which is integrated into the 400 kV AC system.

The HVDC East-South interconnection (commercial operation in 2003) uses both advantages, the avoidance of transmission of additional power through the AC system and the interconnection of power areas which can not be operated synchronously. Fig. 15 shows the geographical location of the DC Interconnector and its main data. A view of the HVDC southern terminal in the industry region of Bangalore is given in Fig. 16.

In April 2006, Siemens has been awarded an order by Powergrid Corporation of India to increase the transmission capacity of the East-South DC transmission from 2000 MW to 2500 MW. After the upgrade is completed, it will be possible to make maximum use of the system’s overload capacity. To increase the capacity of the link, the Siemens experts have developed a solution known as Relative Aging Indication and Load Factor Limitation (RAI & LFL). By these means, it will be possible to utilize the overload capacity of the system more effectively without having to install additional thyristors.
Fig. 15: Geographic Map and main Data of Indian East-South Interconnector

Fig. 16: Site View of Indian East-South Interconnector – DC Station Kolar, close to Bangalore
5. HVDC and FACTS in parallel Operation

In Figs. 17-18, an innovative FACTS application of SVC in combination with an existing HVDC for transmission enhancement in Germany is shown.

**Fig. 17: SVC Siems, Germany - Support of HVDC Baltic Cable**

**Baltic Cable HVDC Link**

Data:
- Germany - Sweden
- Rated power: 600 MW
- Rated voltage: 450 kV DC
- Monopole
- Submarine cable
- Return via earth
- Sea electrodes
- Length: 250 km
- Commissioning: 1994

**Grid reinforcement and SVC for full power operation of the Baltic Cable HVDC link**

**Fig. 18: The Problem – no Right of Way for 400 kV AC Grid Access of Baltic Cable HVDC – and Solutions**

1. **Initial Step for Grid Access Enhancement**
   - 1994 only 110 kV
   - 220 kV Land Cable 350 MVA, 11 km

2. **Final Solution: new SVC with TCR & TSC**
   - 100 MVAr ind.
   - 200 MVAr cap.

3. **Now, the HVDC can operate at full Power Rating**
   - 2004

4. **Substation Siems**
   - Substation Herrenwyk
   - Baltic Cable Connection Station Herrenwyk
   - 600 MW
   - Baltic Cable to Sweden

5. **Baltic Cable HVDC Link**
   - Germany - Sweden
   - Rated power: 600 MW
   - Rated voltage: 450 kV DC
   - Monopole
   - Submarine cable
   - Return via earth
   - Sea electrodes
   - Length: 250 km
   - Commissioning: 1994

**Source:** e-on Netz
It’s a matter of fact that this project is the first high voltage FACTS controller in the German network. The reason for the SVC installation at Siems substation nearby the landing point of the Baltic Cable HVDC were unforeseen right of way restrictions in the neighboring area, where an initially planned new tie-line to the strong 400 kV network for connection of the HVDC was denied. Therefore, with the existing reduced network voltage of 110 kV (see the dotted black lines in Fig. 18), only a limited amount of power transfer of the DC link was possible since its commissioning in 1994, in order to avoid repetitive HVDC commutation failures and voltage problems in the grid. In an initial step towards grid access improvement, an additional transformer for connecting the 400 kV HVDC AC bus to the 110 kV bus was installed (see the figure). Finally, in 2004, with the new SVC equipped with a fast coordinated control, the HVDC could fully increase its transmission capacity up to the design rating of 600 MW. In addition to this measure, a new cable to the 220 kV grid was installed to increase the system strength with regard to performance improvement of the HVDC controls.

In Fig. 19, a view of the Siems SVC in Germany is depicted. Prior to commissioning, intensive studies have been carried out; first with the computer program NETOMAC™ and then with the RTDS™ real-time simulator by using the physical SVC controls and a simplified model for the HVDC.

6. Conclusions

Deregulation and privatization is posing new challenges on high voltage transmission systems. System elements are going to be loaded up to their thermal limits, and wide-area power trading with fast varying load patterns will contribute to an increasing congestion.

Environmental constraints will also play an important role. Additional problems are expected when renewable energies, such as large wind farms, have to be integrated into the system, especially when the connecting AC links are weak and when there is no sufficient reserve capacity in the neighboring system available. In the future, an increasing part of the installed capacity will, however, be connected to the distribution levels (dispersed generation), which poses additional challenges on planning and safe operation of the systems, ref. to Fig. 20.
The loading of existing power systems will further increase, leading to bottlenecks and reliability problems. As a consequence of “lessons learned” from the large Blackouts in 2003, HVDC and FACTS will play an important role for the system developments, leading to “Smart Grids” with better controllability of the power flows (Fig. 21).

Fig. 20: Perspectives of Transmission and Distribution Network Developments

Fig. 21: From Congestion, Bottlenecks and Blackout towards a “Smart Grid”
High voltage power electronics provide the necessary features to avoid technical problems in the power systems, they increase the transmission capacity and system stability very efficiently and they assist in prevention of cascading disturbances.

Bulk power DC transmission will be applied in emerging countries like Brazil, China and India, to serve their booming energy demands efficiently.

In conclusion to the previous considerations, Table 1 summarizes the impact of HVDC and FACTS on load flow, stability and voltage quality when using different devices. For comparison, mechanically switched devices (MSC/R) are included in the table. The evaluation is based on a large number of studies and experiences from projects.

<table>
<thead>
<tr>
<th>Principle</th>
<th>Devices</th>
<th>Scheme</th>
<th>Impact on System Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variation of the Line Impedance: Series Compensation</td>
<td>FSC (Fixed Series Compensation)</td>
<td><img src="image1" alt="Diagram" /></td>
<td><img src="image2" alt="Impact" /></td>
</tr>
<tr>
<td></td>
<td>TPSC (Thyristor Protected Series Compensation)</td>
<td><img src="image3" alt="Diagram" /></td>
<td><img src="image4" alt="Impact" /></td>
</tr>
<tr>
<td></td>
<td>TCSC (Thyristor Controlled Series Compensation)</td>
<td><img src="image5" alt="Diagram" /></td>
<td><img src="image6" alt="Impact" /></td>
</tr>
<tr>
<td>Voltage Control: Shunt Compensation</td>
<td>MSC/R (Mechanically Switched Capacitor / Reactor)</td>
<td><img src="image7" alt="Diagram" /></td>
<td><img src="image8" alt="Impact" /></td>
</tr>
<tr>
<td></td>
<td>SVC (Static Var Compensator)</td>
<td><img src="image9" alt="Diagram" /></td>
<td><img src="image10" alt="Impact" /></td>
</tr>
<tr>
<td></td>
<td>STATCOM (Static Synchronous Compensator)</td>
<td><img src="image11" alt="Diagram" /></td>
<td><img src="image12" alt="Impact" /></td>
</tr>
<tr>
<td>Load-Flow Control</td>
<td>HVDC (B2B, LDT)</td>
<td><img src="image13" alt="Diagram" /></td>
<td><img src="image14" alt="Impact" /></td>
</tr>
<tr>
<td></td>
<td>UPFC (Unified Power Flow Controller)</td>
<td><img src="image15" alt="Diagram" /></td>
<td><img src="image16" alt="Impact" /></td>
</tr>
</tbody>
</table>

Based on Studies & practical Experience

Table 1: FACTS & HVDC – Overview of Functions & “Ranking”

Influence: *

<table>
<thead>
<tr>
<th>Influence</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>○</td>
<td>no or low</td>
</tr>
<tr>
<td>●</td>
<td>small</td>
</tr>
<tr>
<td>●●</td>
<td>medium</td>
</tr>
<tr>
<td>●●●</td>
<td>strong</td>
</tr>
</tbody>
</table>