PERSPECTIVES OF HVDC AND FACTS FOR SYSTEM INTERCONNECTION AND GRID ENHANCEMENT

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Presentation in two Parts:
- DC and AC Technology Issues for Bulk Power EHV and UHV Transmission
- Power System Expansion with Advanced Technologies - Solutions for a "Smart Grid"
0. Introduction

The growth and extension of AC systems and consequently the introduction of higher voltage levels have been driven by a fast growth of power demand over decades. Power systems have been extended by applying interconnections to the neighboring systems in order to achieve technical and economical advantages. Large systems came into existence, covering parts of or even whole continents, to gain the well known advantages, e.g. the possibility to use larger and more economical power plants, reduction of reserve capacity in the systems, utilization of the most efficient energy resources, as well as to achieve an increase in system reliability. In the future of liberalized 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, and also taking into account ecological constraints such as nuclear and hydro-power stations at suitable locations, solar energy from desert areas and embedding of large off-shore wind farms.

The interconnected systems are becoming extremely large and innovative solutions will be essential to avoid congestion and to improve the system stability. Examples of large AC interconnections are systems in Brazil and Asia, as well as in North America, Europe and Russia. However, there are technical and economical limitations in the interconnections if the energy has to be transmitted over extremely long distances through the interconnected synchronous AC systems. In future, the loading of existing power systems will strongly increase, leading to bottlenecks and reliability problems. System enhancement will be essential to balance the load flow and to get more power out of the existing grid in total. Large blackouts in America and Europe confirmed clearly that the favorable close electrical coupling of the neighboring systems might also include the risk of uncontrollable cascading effects in large and heavily loaded synchronous systems.

HVDC (High Voltage Direct Current) transmission and FACTS (Flexible AC Transmission Systems) have developed to a mature technology 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.

In the paper, benefits of bulk power transmission solutions with HVDC and FACTS for system enhancement and grid interconnection are depicted, and UHV applications for AC and DC are presented. Study and project examples using HVDC and FACTS are given and prospects of VSC (Voltage-Sourced Converters) applications are discussed.

1. Development of Power Systems

The development of electric power supply began more than one hundred years ago. Residential areas and neighboring establishments were at first supplied by DC via short lines. At the end of the 19th century, however, AC transmission was introduced, utilizing higher voltages to transmit power from remote power stations to the consumers.

The growth and extension of AC systems and consequently the introduction of higher voltage levels have been driven by a fast growth of power demand over decades. Global studies show that power consumption in the world follows closely the increase of population. In the next 20 years, power consumption in developing and emerging countries is expected to increase by 220 %, in industrialized countries, however, only by 37 %.
In Europe, 400 kV became the highest voltage level, in Far-East countries mostly 550 kV, and in America 550 kV and 765 kV. The 1150 kV voltage level was anticipated in the past in some countries, and also some test lines were already built. Fig. 1 and 2 depict these developments and perspectives.

However, some Countries will finally “go” ≥ 1 GV

Fig. 1: Development of AC Transmission - Milestones

- Voltage Levels of 735 kV to 765 kV AC have been introduced in the following Countries:
  - Canada, Brazil, Russia (USSR), South Africa, South Korea, U.S.A. and Venezuela
- UHV Transmission Lines (1000 kV and above) have been built in Russia and Japan
  - Ekibastuz – Kokchetav (500 km)
  - Kokchetav – Kustanay (400 km)
  - Minami – Niigata / Nishi – Gunma (200 km)
  - Kita – Tochigi / Minami – Iwaki (250 km)
- However, today these UHV Transmission Lines are operated at 500 kV

Fig. 2: Development of EHV and UHV AC Transmission - Status and Perspectives

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 of power systems has 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.

Such problems are even deepened by the deregulation of the electrical power markets, where contractual power flows do not follow the design criteria of the existing network configuration, see Fig. 3.

Fig. 3: Trends in High Voltage Transmission Systems

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, power electronics can clearly strengthen the power systems and improve their performance.

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. 4 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 so-called “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. 5 depicts how these ideas of hybrid interconnections are reflected in China's grid development.

**Fig. 5: Perspectives of Grid Developments in China - AC & DC Bulk Power Transmission from West to East via three main Corridors**

... the installed Generation Capacity will be 900 GW

Sources:

**Fig. 4: Large Power System Interconnections - Benefits of Hybrid Solutions**

Fig. 5 depicts how these ideas of hybrid interconnections are reflected in China's grid development.
Focus is on interconnection of 7 large inter-provincial grids of the Northern, Central and Southern systems via three bulk power corridors which will build 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 are also some 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 FACTS controllers for power oscillation damping and stability support are in discussion.

2. Transmission Solutions with HVDC and FACTS

In the second half of the past century, High Voltage DC Transmission (HVDC) was introduced, offering new dimensions for long distance transmission. This development started with the transmission of power of ratings of a few hundred MW. By these developments, HVDC became a mature and reliable technology. Up to now, over 55 GW HVDC transmission capacities have been installed worldwide, see Fig. 6.

![Graph showing development of DC Transmission - Worldwide installed Capacity](image)

**Worldwide installed HVDC “Capacity”: 55 GW in 2005**

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. 6: Development of DC Transmission - Worldwide installed Capacity**
It can be seen that China alone will be contributing significantly to this development because of its rapidly growing economy (GDP) every year.

Transmission distances over 1000 to 2000 km or even more are possible with DC overhead lines. In general, for transmission distances above 700 km, DC transmission is more economical than AC transmission (≥ 1000 MW). With submarine cables, transmission levels of up to 600 - 800 MW over distances of nearly 300 km have already been attained, and cable transmission lengths of up to 1,300 km are in the planning stage. Transmission ratings of 3 GW over large distances with just one bipolar DC line are state-of-the-art in many grids today. As a multi-terminal system, HVDC can also be connected at several points with the surrounding AC networks.

In Fig. 7 and 8, the transmission grid developments in China and India are depicted, leading to very large hybrid interconnections with AC and DC solutions, including FACTS.

Initially:
Gezhouba-Shanghai
TianGuang
3G-ECPG I
GuiGuang I
3G-Guangdong
GuiGuang II

plus
3 x B2B and
11 x HVDC
Long Distance Transmissions

2005: 12 GW
2020: 60 GW

Sources: SP China, ICPS - 09/2001; State Grid Corp. China, 2003

Fig. 7: China goes Hybrid - AC plus 20 HVDC Interconnections

Since the 60s Flexible AC Transmission Systems have been being developed to a mature technology with high power ratings. Excellent operating experiences are available worldwide and the technology became mature and reliable. FACTS, based on power electronics, have been developed to improve the performance of weak AC Systems and for long distance AC transmission.

FACTS can, however, also contribute to solve technical problems in the interconnected power systems. FACTS are applicable in parallel connection (SVC, Static VAR Compensator - STATCOM, Static Synchronous Compensator), in series connection (FSC, Fixed Series Compensation - TCSC/TPSC, Thyristor Controlled/Protected Series Compensation - S³C, Solid-State Series Compensator), or in combination of both (UPFC, Unified Power Flow...
Controller - CSC, Convertible Static Compensator) to control load flow and to improve
dynamic conditions. GPFC is a special DC back-to-back link, which is designed for fast
power and voltage control at both terminals. In this manner, GPFC is a “FACTS B2B”, which
is less complex and less expensive than the UPFC. Rating of SVCs is up to 800 MVAr, series
FACTS devices are implemented on 550 and 735 kV levels to increase the line transmission
capacity up to several GW. A large number of different FACTS and HVDC controllers have
been put into operation either as commercial projects or prototypes. Recent developments are
the TPSC (Thyristor Protected Series Compensation) and the Short-Circuit Current Limiter
(SCCL), both innovative solutions using special high power thyristor technology.

3. Power Electronics for FACTS and HVDC

FACTS and HVDC use power electronic components and conventional equipment which can
be combined in different configurations for switching or controlling reactive power, and for
active power conversion. Conventional equipment (e.g. breakers, tap-changer transformers)
offer very low losses, but the switching speed is relatively low. Power electronics can provide
high switching frequencies up to several kHz, however, with an increase in losses. A view on
the different kinds of semiconductors is given in Fig. 9. In Fig. 10, the stepwise assembly of
the thyristors in modules and valve groups is shown. Fig. 11 indicates the typical losses
depending on the switching frequency.
From Fig. 11, it can be seen that – due to less losses – the preferred solution for Bulk Power Transmission is in fact the line-commutated thyristor technology. The today’s losses of high power VSCs (Voltage-Sourced Converters) with high switching frequencies are within the range of 4 - 5 %, which is too much for very large transmission projects.
4. Projects with HVDC and FACTS for Power System Enhancement

In Fig. 12, the features and cost savings of series compensation for a large transmission project in Brazil (TCSC Serra da Mesa, on a 1000 km AC line) due to grid enhancement are summarized. The mentioned SSR (subsynchronous resonances) topic is a critical issue for large thermal generators with long shafts.

Fig. 12: 500 kV TCSC Serra da Mesa, Furnas/Brazil – Essential for Transmission

The flexibility of modern FACTS technologies under extremely harsh environmental conditions is indicated in the figure: the operating range for the TCSC can reach up to $+85^\circ$ C.
This is necessary due to the outdoor installation on high voltage potential, with the isolated platform mounted directly in series with the transmission line.

Figs. 13-14 give an example of system studies for large projects in China, in which both FACTS and HVDC have been integrated for grid interconnection and point-to-point long distance transmission in a hybrid way.

Because of the long transmission distances, the system experiences severe power oscillations after faults, close to the stability limits. In the recordings in Fig. 14 oscillations are depicted. The first case given is HVDC transmitting power in constant power mode, see curve a. It can be seen that strong power oscillations occur. If, however, damping control of HVDC Gui-Guang is activated (curve b), the oscillations are damped very effectively.

Using series compensation with two TCSCs and two FSCs at Pingguo substation, the stability of the overall system can be further increased (curve c). Without series compensation and...
without HVDC damping, a power system as large as this one would be unstable in case of fault contingencies, consequently leading to severe outages (Blackout). Stability studies have been carried out with the Siemens computer program NETOMAC, followed by intensive digital Real-Time Simulator tests with RTDS™.

Fig. 15 shows the highlights of the HVDC Gui-Guang project, for which the POD scheme is applied.

Fig. 15: Highlights of the Gui-Guang HVDC Transmission Project

Similar studies for HVDC and FACTS in parallel operation have been carried out for a number of large transmission projects worldwide.

5. 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. 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, ref. to Fig. 8. AC, they will, however, realize with EHV levels up to 800 kV.

An overview of existing UHV AC transmission schemes was presented in Fig. 2, section 1. The figure shows, that – up today – all of these installations are now operating at a reduced voltage of 500 kV. There are both technical and financial reasons, e.g. grid coupling transformers using 500 kV are much cheaper. However, a lot of experience has been gained and the engineers are ready for new challenges. China’s government undertakes strong efforts, to overcome all outstanding issues – in close co-operation with international manufacturers.

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. 16-17 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

Works for 800 kV DC Transformer

Fig. 16: Transformer for UHV DC – In the State of Development

An example of the complete HVDC station layout is given in Fig. 18.

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.
Fig. 17: UHV DC Bushing at Test Lab TU Graz – Austria

Fig. 18: Fully redundant HVDC Scheme – with two 400 kV 12-Pulse Converters per Pole
A major benefit of this solution, as shown in Fig. 18, 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. 19.

![Figure 19: Valve Hall Configuration – for 800 kV HVDC](image)

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**

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.

Based on the discussions and descriptions, following summary and 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

6. Prospects of the Brazilian Grid Development

In Brazil, there is a huge need for further system interconnections, both within the national grid, and to the neighboring countries. Reasons for this are as follows: strong increase in regenerative energy sources in Brazil, as well as creating new import and export capabilities to the neighbors to meet the booming energy demand in the region.

Fig. 20: Development of Hydro Generation in Brazil

Fig. 20 highlights the development of hydro sources in Brazil. Main increase in generation capacity will be driven by two projects: first Rio Madeira and, at a later stage also by Belo Monte. For these two projects different options for both AC and hybrid DC solutions are under investigation.
Fig. 21 depicts an example of study alternatives for Belo Monte, and Figs. 22-23 represent some of the alternatives for the Rio Madeira project, which are currently developed by EPE.

Fig. 21: AC-DC Study Alternatives for new Power Plant – Belo Monte

Fig. 22: Initial Option of 750 kV AC Interconnection for Rio Madeira Project
The hybrid solution, as shown in Fig. 23, is the most promising alternative for Rio Madeira, by using the power oscillation damping features of the HVDC.

**Fig. 23: Hybrid AC-DC Options for Rio Madeira Project**

In the on-going studies, it will be further investigated, whether a new 500 kV AC double line or even the existing 230 kV transmission grid can be used. An additional B2B nearby the Rio Madeira substation is also under consideration as a “flexible” interconnector to the surrounding AC grid. Key-issue of the Rio Madeira project will be the use of a large number of relatively small bulb generation units (each with ratings of 40 to 70 MW only) which have a very low inertia time constant in the range of 1 to 2 s only.

In addition to this, if the interconnection uses the existing 230 kV AC system without implementation of a new 500 kV or 750 kV AC “backbone”, the overall system stability will be a crucial issue.

In the Cahora Bassa project (Fig. 24), similar stability issues were investigated, when a large HVDC was operating in parallel with a very weak 330 kV AC system. The solution consisted in the implementation of the GMPC (Grid Master Power Controller) which provided coordinated control and damping facilities for the HVDC to stabilize the parallel AC system as well as for remote system re-synchronization after AC line tripping. This was done by means of GPS-satellite synchronized AC system phase angle measurements, as shown in the figure.

The option for a use of thyristor switched braking resistors (TSBR) at Cahora Bassa hydro power plant was also investigated during the stability studies. However, in the end, they were not implemented in the project, because the HVDC Performance was good enough even without TSBR, and the inertia time constant of the large hydro generators (484 MW each) was not a crucial issue.
7. Conclusions – With High Voltage Power Electronics towards a “Smart Grid”

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. 25.

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, FACTS and HVDC will play an important role for the system developments, leading to “Smart Grids” with better controllability of the power flows (Fig. 26).

FACTS and HVDC provide the necessary features to avoid technical problems in the power systems, and 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.

Fig. 25: Perspectives of Transmission and Distribution Network Developments

Fig. 26: From Congestion, Bottlenecks and Blackout towards a “Smart Grid”