Use of FACTS and HVDC for Power System Interconnection and Grid Enhancement

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0. Overview

Interconnection of power systems with either AC or DC links 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 stations, sharing of spinning reserve, use of most economic energy resources, as well as ecological constraints: nuclear power stations at selected locations, hydro energy from remote areas, solar energy from steppes and deserts, and connection of large off-shore wind farms.

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. Up to now, the power systems in China are more separated: China with 7 large inter-provincial grids and India with 4 large regional grids. However, interconnections by AC and increasingly by DC are in progress in Far East, too.

Since the 60s, FACTS (Flexible AC Transmission Systems) and HVDC (High Voltage Direct Current) transmission have developed into a mature technology with high power ratings. Transmission ratings of 3 GW over large distances with just one bipolar DC transmission system are state of the art in many grids today. In China, however, there are new transmission schemes in the planning phase with ratings of 4 - 6 GW (at +/- 800 kV DC and 1000 kV AC). Reason for such high ratings is the need for bulk power transmission corridors with 20 GW for system interconnection.

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. As a multi-terminal system, HVDC can also be connected at several points with the surrounding AC networks. FACTS is applicable in parallel connection (SVC, Static VAR Compensator – STATCOM, Static Synchronous Compensator) or in series connection (FSC, Fixed Series Compensation - TCSC, Thyristor Controlled Series Compensation – TPSC, Thyristor Protected Series Compensation) or in combination of both (UPFC, Unified Power Flow Controller) to control load flow and to improve dynamic conditions. Rating of SVCs is up to 800 MVAR, series FACTS devices are implemented on 550 and 735 kV level to increase the line transmission capacity up to several GW.
In the paper, benefits of FACTS and HVDC for system interconnection and for grid enhancement are depicted, and preferences of applications are explained. Study and project examples are given.

1. Development of Power Transmission

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 complexity of power systems has grown. This development is schematically shown in Fig. 1.

![Fig. 1: Development of Power Systems and per Capita Consumption](image)

To transport the energy from generation to consumers, the development of power systems considers locations of expected load requirements on the one hand, and the suitable location of power stations on the other hand. However, on a long-term basis, it can be expected that the transmission systems will stagnate in their development, since an increasing part of power generation will be transferred into the distribution or low voltage networks in the future [1, 3].

Since the load flows existing today can change considerably, this altering environment decisively influences further development and optimization of transmission networks. The ancillary functions required for smooth operation of the networks, such as frequency control, load-flow control, reactive-power and voltage control, as well as the responsibility for system
security, are in the hands of the system operator. To support the operation and to increase the reliability of heavily loaded networks, FACTS and HVDC need to be installed. Higher investments into grid interconnections must be made to achieve cost benefits.

Based on a large number of studies on power system development in different world regions, the following general trends can be expected:

- **Increasing Power Demand - from 3,560 GW in 2000 to 5,700 GW in 2020**
- **Strong Environmental Constraints – Limitation for Power Plant Expansions**
- **Natural Energy Resources far away from Load Centers**
- **Severe Right of Way Constraints**
  - A strong Issue in many Countries, especially in Europe

As listed below, power system interconnections offer the necessary benefits regarding these constraints. They are generally valid and do not depend on the kind of the interconnection.

- **Possibility to use larger and more economical Power Plants**
- **Reduction of the necessary Reserve Capacity in the System**
- **Utilization of most favorable Energy Resources**
- **Flexibility of building new Power Plants at favorable Locations**
- **Increase of Reliability in the Systems**
- **Reduction of Losses by an optimized System Operation**

With the size of interconnected systems, however, the technical and economical advantages diminish and the required additional investments for system enlargements increase. In addition to that, the transmission costs increase with the transmission distance. Considering the current transmission costs of about 1-2 Cents per kWh and 1000 km, the advantages of the energy taken from the interconnected systems over very long distances would not be economical any more. The reasonable distance to transmit power still economically could be therefore in the range of up to 3000 km. These conditions, however, could possibly change if strong political efforts will support the use of renewable energy in remote areas in large scale, independent from production and transmission costs. Strategies for the development of large
power systems go clearly in the direction of hybrid transmissions, consisting of HVDC and HVAC interconnections among regional sub-systems. Such interconnected systems have significant technical and reliability advantages [3-6].

Fig. 2 shows schematically such a hybrid system using HVDC and FACTS. Power exchange in the neighboring areas of interconnected systems offering most advantages can be realized by AC links, preferably including FACTS for increased transmission capacity and for stability reasons. The transmission of larger power blocks over longer distances should, however, be utilized by the HVDC transmissions directly to the locations of power demand. HVDC can be realized as direct coupler without a DC line – the so-called Back-to-Back solution (B2) 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 [3, 6].

Long-term developments in power industry depend on expectations for future political, financial and technical conditions. For the last decade, however, the developments have been strongly driven by the globalization, leading to deregulation and liberalization. The world markets have been gradually opened, with different speed in different countries. This transition of economies brought many advantages, but also disadvantages in some fields. At
the same time, social and environmental aspects became more and more important, even if they are, in some way, in contradiction with the globalization of the economy.

**Fig. 3: Investments in Power Industry**

Fig. 3 shows the typical sharing of investments in power generation, transmission and distribution. These values depend, however, on the specific structure of the systems. The estimation of the requested investments in the power industry for the next 30 years is US$ 10 trillion, or roughly US$ 350 billion per year. Based on this, about US$ 70 billion per year should be invested in power transmission [1].

**Fig. 4: Transmission Systems – The “VIPs” of the Power Market**
Although the sharing of transmission investments is only 20% of the total sum, its importance is in fact high: transmission can be the key for cash-flow and return on investments, or just a bottleneck causing limitations and supply interruptions. Thus, transmission systems are the VIPs of the power market, as shown in Fig. 4.

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

**Fig. 5: Development of DC Transmission: Worldwide installed Capacity**

Fig. 5 shows the perspectives of DC transmission capacity worldwide. It can be seen that China alone will be contributing significantly to this development because of its large increase of economy (GDP) per year.

In Fig. 6 and 7, the transmission grid developments in China and India are depicted, leading to very large hybrid interconnections with AC and DC solutions.

A large number of different FACTS and HVDC have been put into operation either as commercial projects or prototypes. Fig. 8 gives an example of the Siemens applications worldwide. Thus it appears that some areas are still “blank”, which is expected to change in the future. In the figure, the number and the increase of large HVDC long-distance transmission projects are also indicated.

The different technologies with FACTS and HVDC for grid enhancement using modern high power electronics, as indicated in Fig. 8, are explained more detailed in the next sections.
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. 6: China goes Hybrid: AC plus 20 HVDC Interconnections

DEVELOPMENT OF NATIONAL GRID

PHASE - III
(By 2012)

Similar Perspectives
... as in China

Source: Power Grid Corporation of India, 2003

Fig. 7: Grid Extension in India - Hybrid AC plus DC
2. Transmission Solutions with 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 slow. Power electronics can provide high switching frequencies up to several kHz, but 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. 9: High Power Semiconductors

Fig. 8: FACTS & HVDC worldwide – Example Siemens (ref. to Text)
Fig. 11: Use of Power Electronics for FACTS & HVDC - Transient Performance and Losses

More Dynamics for better Power Quality:
- Use of Power Electronic Circuits for Controlling $P$, $V$ & $Q$
- Parallel and/or Series Connection of Converters
- Fast AC/DC and DC/AC Conversion

Transition from “slow” to “fast”

On-Off Transition 20 - 80 ms

Thyristor 1-2 %
GTO
IGBT / IGCT > 1000 Hz

Switching Frequency:
50/60 Hz
< 500 Hz

Losses

Fig. 10: HVDC and FACTS - Advanced Power Electronics for High Voltage Systems
The dependency between transient performance and losses is depicted in Fig. 11. An example of actual losses in a large HVDC project is given in section 5, Fig. 26.

Flexible AC Transmission Systems (FACTS) based on power electronics have been developed to improve the performance of long distance AC transmission. The technology has then been extended to the devices which can also control power flow. Excellent operating experiences are available worldwide, and FACTS technology also became mature and reliable.

Fig. 12 shows the principal configurations of FACTS devices. Main shunt connected FACTS application is the Static Var Compensator with line-commutated thyristor technology, where the maximum switching frequency in each phase element is limited by the “driving” system frequency.

- **SVC** - Static Var Compensator (Standard for Parallel Compensation)
- **STATCOM** - Static Synch. Compensator (Fast SVC, Flicker Compensation)
- **FSC** - Fixed Series Compensation
- **TCSC** - Thyristor Controlled Series Compensation
- **TPSC** - Thyristor Protected Series Compensation
- **GPFC** - Grid Power Flow Controller (FACTS-B2B)
- **UPFC** – Unified Power Flow Controller

![Fig. 12: FACTS - Flexible AC Transmission Systems: Support of Power Flow](image)

A further development is STATCOM using voltage sourced converters. Both devices provide fast voltage control, reactive power control and power oscillation damping features (POD). As an option, SVC can control unbalanced system voltages. The developments of FACTS technologies are depicted in Fig. 13. Static Var Compensation is mainly used to control system voltage. There are hundreds of these devices in operation worldwide. For decades, it has been a well developed technology, and the demand on SVC is further increasing.

Fixed series compensation is widely used to improve the stability by reducing the transmission angle in long distance transmissions. A huge number of these applications are in operation. If system conditions are more complex, Thyristor Controlled Series Compensation
is used. TCSC has already been applied in different projects for load-flow control, stability improvement and to damp oscillations in interconnected systems.

Special FACTS devices are UPFC (Unified Power Flow Controller) and GPFC (Grid Power Flow Controller) [2, 5]. UPFC combines a shunt connected STATCOM with a series connected STATCOM (= $S^3C$, Solid State Series Compensator), which can exchange energy via a coupling capacitor. The CSC (Convertible Synchronous Compensator) in Fig. 8 uses a UPFC which can be switched over into different applications with either two STATCOMs or two $S^3Cs$. 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 Back-to-Back”, which is less complex and expensive than the UPFC.

For most applications in AC transmission systems and for network interconnections, SVC, FSC, TCSC and GPFC/B2B are fully sufficient to match the essential requirements of the grid. STATCOM and UPFC are tailored solutions for special needs.

The basic configurations of HVDC are depicted in Fig. 14 and 15. HVDC operates as power flow controller; it “forces P to flow”. In hybrid system configurations with synchronous frequencies over the whole grid, HVDC offers a highly effective control of power flow. In addition to that, in case of system faults, HVDC can either support the grid recovery, or it can automatically split the systems like a “Firewall”, which is very helpful for Blackout

**Fig. 13: FACTS – Technology Developments**

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prevention in case of cascading events [3]. For bipolar applications, a second set of converters with negative voltage plus coupling transformers is provided.

For system interconnections, an additional benefit of the HVDC is its incorporated fault-current limitation feature. HVDCPLUS 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 by use of voltage sourced converters. Voltage sourced
converters do not have the need of 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.

3. Phase Shifting Transformer versus HVDC and FACTS

Phase shifting transformers have been developed for transmission system enhancement in steady state system conditions. The operation principle is voltage source injection into the line by a series connected transformer, which is fed by a tapped shunt transformer, very similar to the UPFC, which uses VSC-Power Electronics for coupling of shunt and series transformer. This way, overloading of lines and loop-flows in Meshed Systems and in parallel line configurations can be eliminated. However, the speed of phase shifting transformers for changing the phase angle of the injected voltage via the taps is very slow: typically between 5 and 10 s per tap, which sums up for 1 minute or more, depending on the number of taps.

As a rule of thumb for successful voltage or power-flow restoration under transient system conditions, a response time of approx. 100 ms is necessary with regard to voltage collapse phenomena and “First Swing Stability” requirements. Such fast reaction times can easily be achieved by means of FACTS and HVDC controllers. Their response times are fully suitable for fast support of the system recovery. Therefore, dynamic voltage and load-flow restoration is clearly reserved to power electronic devices like FACTS and HVDC.

In conclusion, phase shifting transformers and similar devices using mechanical taps can only be applied for very limited tasks with slow requirements under steady state system conditions.

4. FACTS Technologies and Applications

In this section, a more detailed description of FACTS technologies is given. Fig. 16 and 17 show the full range of applications, including actual ratings and voltage levels of today’s solutions, as listed in Fig. 8.

Fig. 18 shows a site view of one of the 27 SVCs, which have been installed in the UK to overcome transmission bottlenecks caused by deregulation [3]. The SVC control functions, including options for specific tasks, such as unbalance control (not necessary in UK), are also indicated in the figure. An increasing number of SVCs are also going to be installed in other continents. In Fig. 19, an example of an SVC in South America is given. The SVC was implemented to improve system stability of the large transmission grid. The installed containerized solution offers additional benefits, such as reduction in installation and
commissioning time, as well as space and cost savings compared to conventional building technologies.

Fig. 16: FACTS for Parallel Compensation

Fig. 17: FACTS for Series Compensation
In Fig. 20-21, the features and cost savings of series compensation due to grid enhancement are summarized. The mentioned SSR (sub-synchronous resonances) topic is a critical issue for large thermal generators with long shafts [7]. The flexibility of modern FACTS technologies under extremely harsh environmental conditions is indicated in Fig. 21-22: the operating range for FSC begins at -50°C, for TCSC it can reach up to +85°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.

**Fixed Series Compensation:**
- Increase of Transmission Capacity

**Controlled Series Compensation:**
- Damping of Power Oscillations
- Load-Flow Control
- Mitigation of SSR

**Fig. 20: FACTS - Application of Series Compensation**

- Current Control
- Impedance Control
- Power Oscillation Damping (POD)
- Mitigation of SSR (Option)

- Up to 500 POD Operations per day for saving the System Stability
- A System Outage of 24 h hours would cost 840,000 US $ *

- 25 US $/MWh x 1400 MW x 24 hrs

**Benefits:**
- Increase of Transmission Capacity
- Improvement of System Stability

**Fig. 21: 500 kV TCSC Serra da Mesa, Furnas/Brazil – Essential for Transmission**

**Fig. 22: FSC at EHV 735 kV plus harsh Environment**
For Thyristor Protected Series Compensation TPSC, innovative developments in Thyristor-Technology have been applied: Light-triggered Thyristors (now state of the art for FACTS and HVDC) by means of a special heat-sink to enable a very fast self-cooling of the valves within half a second only. By these means, TPSC is fully suitable for multiple fault conditions, as it is often the case under hot climate conditions due to brush-fires leading to repetitive line faults. In the TPSC, the thyristor replaces the conventional MOV (zinc oxide arrester) for fast capacitor protection against over voltages due to short-circuit currents. During faults, the MOV heats up heavily. Due to an upper temperature limit, the MOV must cool down before the next current stress can be absorbed. Cool-down requires a substantial amount of time, time constants of several hours are typical. During this time, the series compensation must be taken out of service (bypass-breaker closed) and consequently the power transfer on the related line needs to be reduced dependent on the degree of compensation, leading to a significant loss in transmission capacity. Thus it appears that by using the TPSC with fast cooling-down time instead of conventional series compensation with MOV, a significant amount of money for each application can be saved.

Fig. 23 shows a site-view of one of the 5 TPSCs, installed at 500 kV in California, USA (ref. to Fig. 8).

In Fig. 24, two projects with series compensation in China are presented. The picture a) gives a view of one phase element of the two Pingguo TCSCs. The 3D view b) demonstrates how
easily series compensation can be mounted to the existing line: when the installation is finished (besides the line), a line interruption and a jumper connection to the platform is made, with an actual power transmission interruption of only 1-3 days.

5. HVDC for Interconnection and Transmission Optimization

During the developments of East-West Grid interconnection in Europe, three B2B projects have initially been installed. One of them is shown in Fig. 25. All 3 projects led to fast and more than full return on investments by energy trading. With the upcoming synchronous extension of UCTE, however, they were taken out of service.

The low losses of the thyristor technology in comparison with VSC devices (ref. to Fig. 11), are depicted in Fig. 26 for the Etzenricht installation shown in Fig. 25. Similar – and even lower – losses have been achieved with the new HVDC installations. Especially in very large DC transmission projects with 3 GW and more, minimal losses are an important issue for the investors.

Fig. 24: China goes ahead – Transmission Enhancement with FACTS
   a) Photo of Pingguo TCSC, commissioned in June 2003
   b) 3D View on Fengjie 500 kV Fixed Series Compensation, China
      2x 600 MVAr, Line Compensation Level 35%
After the Blackout in the United States, new projects with high voltage power electronics are smoothly coming up. Siemens PTD has been awarded a contract by Neptune Regional

Fig. 25: Etzenricht, one of the initial Steps for East-West System Interconnection in Europe with 3 B2Bs – now replaced by synchronous Links (ref. to Text)

Fig. 26: HVDC Losses – Example B2B Etzenricht

After the Blackout in the United States, new projects with high voltage power electronics are smoothly coming up. 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. 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 a single source, Siemens is providing seamless coverage for 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. In Fig. 27, highlights of this innovative project are depicted.

Another highlight of HVDC project development is shown in Fig. 28. Basslink HVDC provides a submarine cable link across the Bass Strait between Tasmania and the state of Victoria on the Australian mainland. Basslink Pty Ltd. was specially formed by National Grid Transco (the world's largest independent transmission network operator) to run the project titled Basslink. The advantages of this link lie on both sides of the water: gaining access to the Australian electricity market, Tasmania can supply Victoria at peak load times with power from hydro generating plants. Tasmania can top up its base load from the mainland grid and

Fig. 27: New HVDC Cable Link Neptune RTS, USA
also secure the base load in drought periods, when reduced hydro power is available. In addition to that, Tasmania plans to set up wind farms to improve the production of electrical power from regenerative sources further, ref. to Fig. 28.

Fig. 28: Innovative Transmission Technologies for long Distances - Basslink HVDC

The Basslink HVDC project shows that HVDC is fully suitable to match complex transmission requirements even under environmental sensitive conditions. In Fig. 29 it is shown that a combination of land cable, sea cable and overhead line was selected to match both environmental constraints and cost issues.

For a long time, China has been benefiting from HVDC transmission by connecting clean and low cost energy sources to the remote load centers, as indicated in Fig. 30 for the Tian-Guang project (1800 MW) in South China. In Fig. 31 it is shown that a project termination for Gui-Guang I (3000 MW) could be achieved 6 months ahead of schedule, which provides a large amount of additional return on investments to the customer.
As a follow-up of the Gui-Guang I project, which is in full commercial operation, a new contract for Gui-Guang II has been awarded to Siemens and its local partners with equal transmission capacity of 3000 MW. Examples of system studies for projects with HVDC and FACTS for system stability improvement in China and other continents are depicted in the next section.
6. System Studies for large Transmission Projects with HVDC and FACTS

Fig. 32-33 give an example of a large power system simulation of the Chinese grid [2], in which both FACTS and HVDC have been integrated for grid interconnection and point to point long distance transmission in a hybrid way.

Fig. 31: HVDC Long Distance Transmission Gui-Guang I

Fig. 32: Use of HVDC and FACTS in a hybrid System in China
Because of the long transmission distances, the system experiences severe power oscillations after faults, close to the stability limits. In the recordings in Fig. 33 (upper part) 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). The lower part of Fig. 33 shows that without HVDC, the Pingguo TCSCs need more actions for damping: 1a) compared to 2a)-b). Without series compensation and without HVDC damping, such a large power system would be unstable in case of fault contingencies, thus leading to severe outages (Blackout) [3].

Fig. 33: China - Benefits of active Damping with HVDC & FACTS
Similar studies have been carried out for large transmission projects worldwide. An example of such studies is described in the following.

With the Mead-Adelanto and the Mead-Phoenix Transmission Project (MAP/MPP), a major 500 kV transmission system extension has been carried out to increase the power transfer opportunities between Arizona and California, USA. The extension includes two main series compensated 500 kV line segments and two equally rated Static Var Compensators, supplied by Siemens, at the Adelanto and Marketplace substations - ref to Fig. 34. The SVCs enabled the integrated operation of the already existing highly compensated EHV AC system and two large HVDC systems. The SVC installation was an essential prerequisite for the overall system stability at an increased power transfer rate.

An example of the intensive project testing with computer and real-time simulator facilities is given in Fig. 35 for a fault application at Marketplace 500 kV bus. The figure shows the computer test results with both SVCs active. The influence of the HVDC can be seen from

Fig. 34: HVDC plus SVC: Mead-Adelanto - USA
the DC voltage $E_{dc}$. Figure a) is with both SVCs only in voltage control mode (PSDC blocked); Figure b) shows an improved damping with the PSDC function enabled.

Fig. 36: A new FACTS application with SVC in combination with HVDC in Germany is shown [2]. It is actually the first high voltage FACTS controller in the German network. 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. 36), 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 first step for grid access improvement, an additional transformer for connecting the 400 kV HVDC AC bus with the 110 kV bus (see the figure) was installed. Finally, in 2003 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. 37, a photo of the Siems SVC in Germany is given.

![Diagram of SVC Voltage- and POD-Control Mode](image)
In the same way as in the previous project cases, intensive studies, first with computer and then with real-time simulator by using the physical SVC controls and simplified models for the HVDC, have been carried out prior to commissioning.

Fig. 36: The Problem – no Right of Way for 400 kV AC Grid Access of Baltic Cable HVDC

Fig. 37: The Solution – the first HV SVC in the German Grid at Siems Substation

In the same way as in the previous project cases, intensive studies, first with computer and then with real-time simulator by using the physical SVC controls and simplified models for the HVDC, have been carried out prior to commissioning.
In conclusion of the previous sections, Table 1 summarizes the impact of FACTS and HVDC on load flow, stability and voltage quality when using different devices. Evaluation is based on a large number of studies and experiences from projects.

<table>
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<th>Principle</th>
<th>Devices</th>
<th>Scheme</th>
<th>Impact on System Performance</th>
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<td>SVC (Static Var Compensator)</td>
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<td>UPFC (Unified Power Flow Controller)</td>
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Based on Studies & practical Experience

**Influence:**
- ○ no or low
- • small
- ● medium
- ○ strong

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

7. Innovative Transmission Solutions using High Voltage Power Electronics

Increasing generation in high load density networks on the one hand, and interconnections among the systems on the other hand, increase the short-circuit power. If the short-circuit current rating of the equipment in the system is exceeded, the equipment must be uprated or replaced, which is a very cost- and time-intensive procedure. Short-circuit current limitation offers clear benefits in such cases. Limitation by passive elements, e.g. reactors, is a well
known practice. It reduces, however, the system stability, and there is an impact on the load-flow.

By combining the previously mentioned 500 kV TPSC application with an external reactor (see Fig. 38), whose design is determined by the allowed short-circuit current level, this device can also be used very effectively as short-circuit current limiter (SCCL, ref. to [4, 7]).

![SCCL diagram](image)

**Fig. 38: SCCL - an Innovative FACTS Solution using TPSC**

This new device operates with zero impedance in steady-state conditions, and in case of short-circuit it is switched within a few ms to the limiting-reactor impedance.

- **Fault Current Limitation**
  - Conventional Solution: Reactor
  - The new FACTS Solution: SCCL
  - Future Option: High-Temperature Superconducting FCL

- **Fault Current Interruption**
  - Is-Limiter
  - Electronic Devices (“Small FACTS”)

**Fig. 39: FCL - Principles and Applications**
Fig. 39 gives a brief overview on today’s solutions for fault-current limitation, including the new SCCL. Basically, there are two methods for fault-current reduction: limitation and interruption. The constraints and benefits of the different solutions are indicated in the figure.

Fig. 40 shows the basic function and the operating principle of the SCCL, including a 3-D view of the SCCL. In comparison with the TPSC site photo, it can be seen that the TPSC is just complemented by an additional reactor for the current limitation. Further details on the SCCL solution are described in [7].

Fig. 40: SCCL - Short-Circuit Current Limitation with FACTS

8. Market and Reliability Issues

Table 2 summarizes the market expectations for FACTS and HVDC solutions today and in the future. The market for series compensation, for SVC and for B2B for load-flow control is actually large today and, as a result of liberalization and deregulation in the power industry, is developing fast in the future. The market in the HVDC long distance transmission field is further progressing fast. A large number of high power long distance transmission schemes using either overhead lines or submarine cables projects have been put into operation or are in the stage of installation.
Concerning reliability of high voltage power electronics, Table 3 gives an example of two SVC projects installed in South Africa. Same high reliability is also achieved for HVDC.

Table 3: Availability of Power Electronics – Example FACTS: close to 100% - same for HVDC

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<td>36h40</td>
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<td>2</td>
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<tr>
<td>Availability (%)</td>
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<td>99.45</td>
<td>100</td>
<td>100</td>
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</thead>
<tbody>
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<td>3h20</td>
<td>4h40</td>
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<td>9</td>
<td>1</td>
<td>2</td>
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<tr>
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<td>62h00</td>
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<tr>
<td>Availability (%)</td>
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<td>99.71</td>
<td>99.92</td>
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</tbody>
</table>

Recordings from NATAL SVCs / RSA (2 TCR & 3 Filter)
Guaranteed Availability: 98 - 99 %
the technology applied uses the same components. Excellent on-site operating experience is being reported, and the FACTS and HVDC technology became mature and reliable.

9. 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 cause congestion. System enhancement will be essential to keep the supply reliable and safe. Interconnection of power systems offers many benefits for the operation of the grids. The performance of power systems, however, decreases with size, loading and complexity of the networks. This is related to problems with load flow, power oscillations and voltage quality. Such problems are even deepened by the changing situations resulting from deregulation of the electrical power markets. The power systems have not been designed for wide-area power trading with daily varying load patterns, where power flows do no more follow the initial planning criteria of the existing network configuration. 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. FACTS and HVDC, however, provide the necessary features to avoid technical problems in the power systems, and they increase the transmission efficiency.

10. References