San José, Costa Rica
November 23 - 28, 2003

THE IERE CENTRAL AMERICA FORUM
"TRANSNATIONAL ELECTRICAL INTERCONNECTIONS AND
SUSTAINABILITY IN CENTRAL AMERICA"

Session Paper

DEVELOPMENT OF FACTS FOR TRANSMISSION SYSTEMS

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Abstract

The performance of power systems decreases with the size, the loading and the 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, where contractual power flows do no more follow the initial design criteria of the existing network configuration.

Additional problems can arise in case of large system interconnections, especially when the connecting AC links are weak. FACTS devices, however, provide the necessary features to avoid technical problems in the power systems and they increase the transmission efficiency.

Keywords:
Development of Power Systems - FACTS Technology - System Stability - Transmission Efficiency

Introduction

The development of Electric Power Industry follows closely the increase of the demand on electrical energy. Main driving factors for energy consumption are listed in Fig. 1. In the early years of power system developments this increase was extremely fast, also in industrialized countries, many decades with the doubling of energy consumption each 10 years. Such fast increase is nowadays still present in the emerging countries, especially in Far-East. In the industrialized countries the increase is, however, only about 1 to 2 % per year with an estimated doubling of the demand in 30 to 50 years.

In next 20 years, power consumption in developing and emerging countries is expected to be doubled, whereas in industrialized countries, it will increase only for about 40 %. Fast development and further extension of power systems can therefore be expected mainly in the areas of developing and emerging countries. However, because of lack on available investments, the development of transmission systems in these countries does not follow the increase in power demand. Hence, there is a gap between transmission capacity and actual power demand, which leads to technical problems in the overloaded transmission systems.

Interconnection of separated grids in the developed countries can solve some of these problems, however, when the interconnections are heavily loaded due to an increasing power exchange, the reliability and availability of the transmission will be reduced.

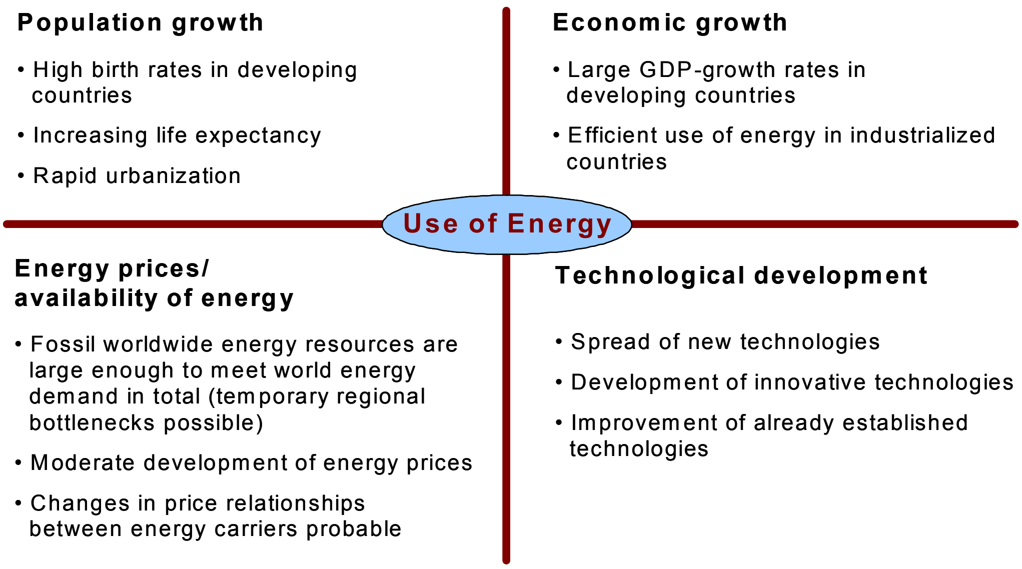


Fig. 1: Main driving Factors for Energy Consumption

In interconnected and long distance transmission systems of industrial and developing countries technical problems can be expected [3-5], which are summarized in Fig. 2. Main problems occur regarding load flow, system oscillations and inter-area oscillations. If systems have a large geographic extension and have to transmit large power over long distances, additional voltage and stability problems can arise.

Interconnected Systems	Long Distance Transmission Systems
o Load Flow Control	o Voltage Control
o Voltage Stability	o Reactive Power Control
o System Oscillations	o Steady-State Stability
o Inter-Area Oscillations	o Dynamic Stability
o Subsynchronous Oscillations	o Subsynchronous Oscillations

Fig. 2: Technical Problems in AC systems

FACTS

System problems listed in Fig. 2 can be improved by FACTS devices. Flexible AC Transmission Systems (FACTS), based on power electronics have been first developed to improve the performance of long distance AC transmission [1]. Later, the technology has been extended to the devices which can also control power flow [2]. Excellent operating experiences are available world-wide and the FACTS technology became mature and reliable.

The main idea of FACTS can be explained by the basic equation for transmission in Fig. 3. Power transmitted between two nodes in the systems depends on voltages at both ends of the interconnection, the impedance of the line and the angle difference between both systems. Different FACTS devices can actively influence one ore more of these parameters and control the power flow through the interconnection.

Fig. 4 shows the principal configurations of FACTS devices. Main shunt connected FACTS application is the Static Var Compensator (SVC) with line-commutated thyristor technology. A further development is STATCOM using voltage source converters. Both devices provide fast voltage control, reactive power control and power oscillation damping features. As an option, SVC can control unbalanced system voltages.

For long AC lines, series compensation is used for reducing the transmission angle, thus providing stability enhancement. The simplest form of series compensation is the Fixed Series Compensation (FSC). Thyristor Controlled Series Compensation (TCSC) is used if fast control of the line impedance is required to adjust the load flow or for damping of power oscillations.

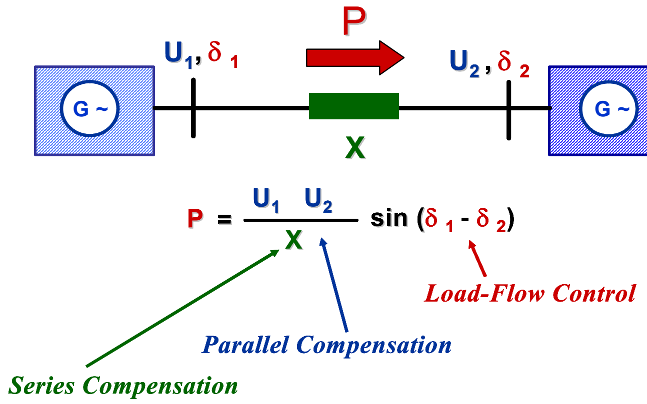


Fig. 3: The Use of FACTS for Power Transmission

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

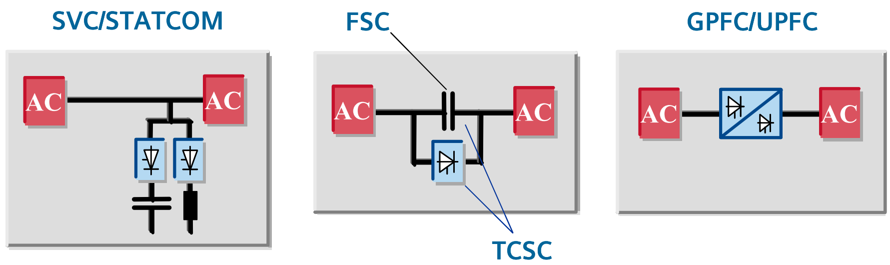


Fig. 4: Basic Configurations of FACTS Devices

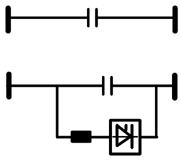
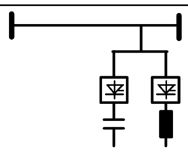
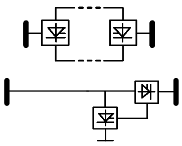
Special FACTS devices are UPFC (Unified Power Flow Controller) and GPFC (Grid Power Flow Controller). UPFC combines a shunt connected STATCOM with a series connected STATCOM, which can exchange energy via a coupling capacitor. GPFC is a simplified DC back-to-back link, which is designed for power and fast voltage control at both terminals. In this way, GPFC is a “FACTS Back-to-Back”, which is less complex than the UPFC at lower costs.

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.

FACTS devices consist of power electronic components and conventional equipment which can be combined in different configurations. It is therefore relatively easy to develop new devices to meat extended system requirements. Such recent developments are the TPSC (Thyristor Protected Series Compensation) and the Short-Circuit Current Limiter (SCCL), both innovative solutions using high power thyristor technology, ref. to section “Innovations in FACTS Technology”.

Fig. 5 summarizes the impact of different FACTS devices on load flow, stability and voltage quality when using different devices. Evaluation is based on large number of studies and experiences from projects. In the same figure, for comparison, also properties of HVDC B2B and Long Distance

Transmission are listed.

Principle	Devices	Scheme	Impact on System Performance		
			Load Flow	Stability	Voltage Quality
Variation of the Line Impedance: Series Compensation	FSC (Fixed Series Compensation) TPSC (Thryristor Protected Series Compensation) TCSC (Thyristor Controlled Series Compensation)		● ● ●●	●●● ●●● ●●●	● ● ●
Voltage Control: Shunt Compensation	SVC (Static Var Compensator) STATCOM (Static Synchronous Compensator)		○ ○	●● ●●	●●● ●●●
Load-Flow Control	HVDC (B2B, LDT) UPFC (Unified Power Flow Controller)		●●● ●●●	●●● ●●●	●● ●●●

Influence: *

○ low or no
● small
●● medium
●●● strong

* Based on Studies & practical Experience

Fig. 5: FACTS - Overview and Functions

A large number of different FACTS devices have been put into the operation either as commercial projects or prototypes. The further market expectations for FACTS and - for comparison - also for HVDC are shown in Fig.6.

Shunt Compensation	SVC	●●●
	STATCOM	●
Series Compensation	FSC	●●●
	TCSC / TPSC	●●
Combined Device	UPFC	●
Power Transmission	HVDC	●●●

●●● Excellent Market
●● Upcoming Market
● Small Market

Fig. 6: Markets of FACTS and HVDC

Static Var Compensation (SVC) is mainly used to control the system voltage. There are hundreds of these devices in operation world-wide. Since decades, it is a well developed technology and the demand on SVC is increasing further. Fixed series compensation is widely used to improve the stability 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.

The market of FACTS equipment for load-flow control is expected to develop faster in the future, as a result of the liberalization and deregulation in the power industry. The market in the HVDC field, however, is further progressing fast. A large number of high power long distance transmission schemes using either overhead lines or submarine cables, as well as back-to-back (B2B) projects have been put into operation or are in the stage of installation.

Use of FACTS in Transmission and Interconnected Systems

Based on the ability to control different system parameters such as voltage, impedance and angle between the system voltages, FACTS can ensure reliable operation of AC transmission up to extremely long distances. Studies showed that it is possible to transmit power over 5 to 6 thousand kilometers. Fig. 7 shows a schematic configuration of such a transmission and the degree of compensation to keep the transmission stable. For such extreme transmission systems, each of the transmission sections needs shunt compensation and controlled series compensation. The operation of such long distance transmission is, of course, possible from technical point of view. The economic aspects of such transmissions are, however, questionable.

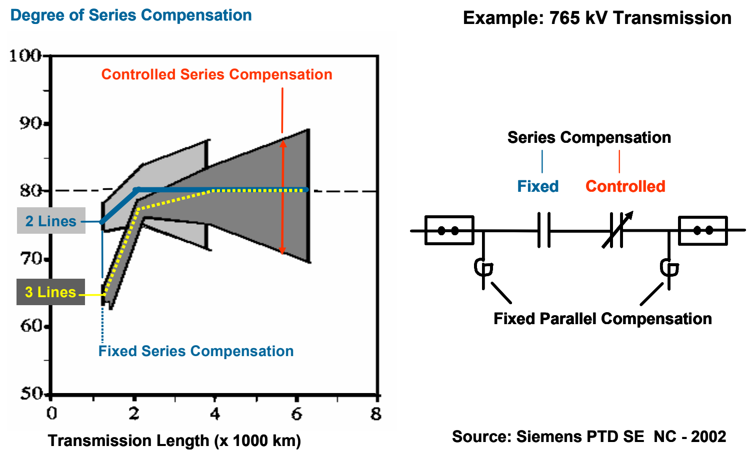


Fig. 7: Limits of long distance AC transmission

Fig. 8 gives an example how FACTS (in this case UPFC or HVDC-B2B as Grid Power Flow Controller) can direct power flow across the interconnection between two systems. If the AC systems are linked at different locations, power loop-flow can occur dependent on the changing conditions in both networks and in case of outages of lines.

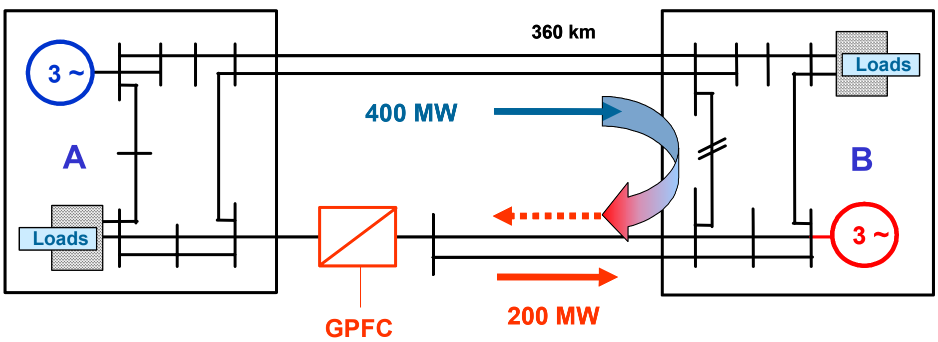


Fig. 8: Avoidance of Loop-Flows with FACTS Grid Power-Flow Controller

In case that power should be transmitted through a meshed system, undesired load flow occur which loads other parts of the system. This can lead to bottlenecks in the system. In such cases FACTS could help to improve the situation.

Fig. 9 shows an example of the West European system: 500 MW should be transported from Hungary to Slovenia. It can be seen, that this power flow is spread widely through the neighboring systems. Only a limited amount of power is flowing directly to the target location. Using a FACTS controller for Grid Power Flow Control, the power exchange between the two countries can be improved significantly.

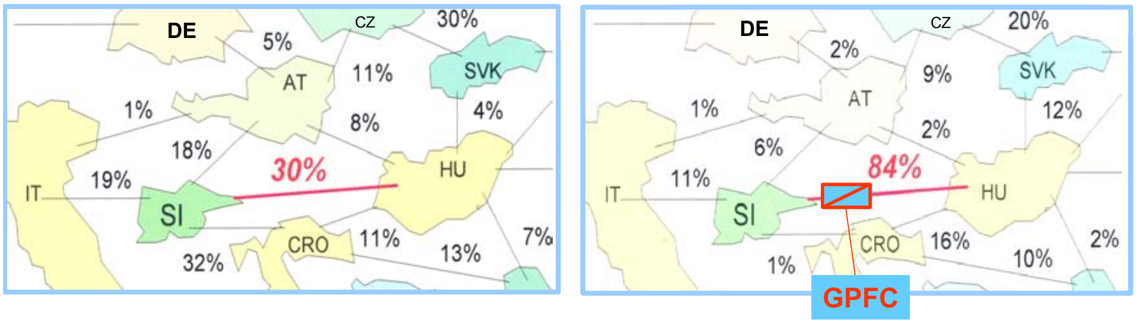


Fig. 9: UCTE – Load-Flow Improvement by means of FACTS

In Fig. 10, simulation results and on-site recordings (by Wide Area Measurement System with GPS) of the European UCTE system show, that an outage of a 300 MW generator in Spain can create large inter-area oscillations in the whole UCTE system. In this case, damping measures by PSS (Power System Stabilizers) at selected locations are still sufficient to avoid large system outages [6]. However, if the UCTE system is increased by new interconnections, additional measures, e.g. by FACTS [2] or HVDC [3] would be necessary for maintaining the stability after disturbances.

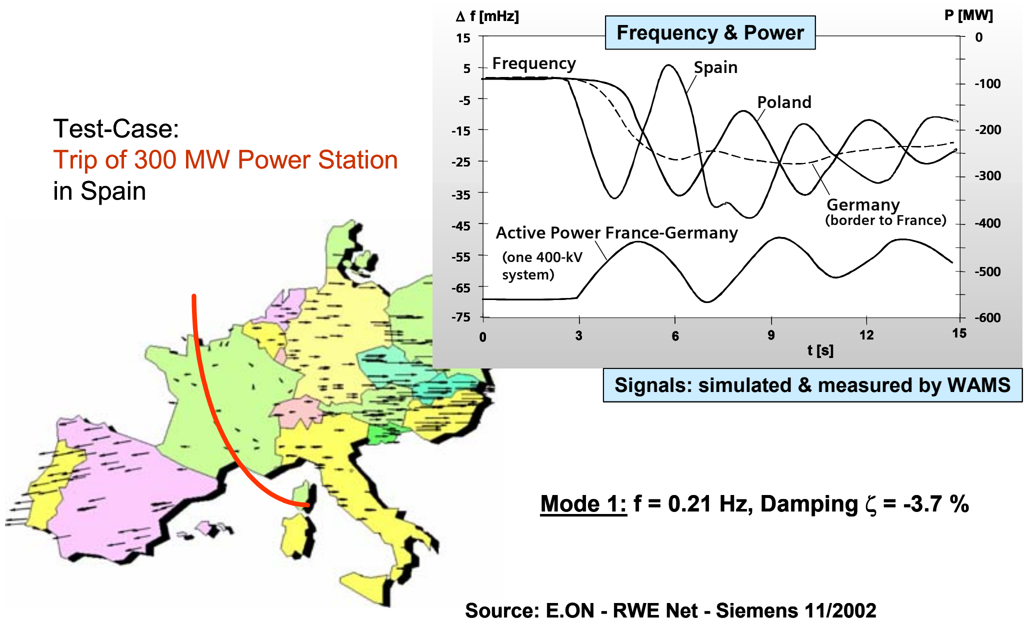


Fig. 10: Interarea-Oscillations in UCTE

In Fig.11 it is shown, how problems with inter-area oscillations have been solved in the Brazilian System. There, the situation is even more critical because of a very long transmission distance between the interconnected systems: a 1000 km 500 kV AC interconnection between North and South systems has been realized. In the interconnection two TCSC devices have been installed at both ends of the line which damp the inherent oscillations that occur between the systems. Additionally, 5 FSC have been necessary to reduce the transmission angle. The recordings from on-site tests show that the interconnection would become unstable without the damping function of TCSC. If only one TCSC is in operation, the interconnection becomes stable, with both devices acting the inter-area oscillations are quite well damped, and redundancy is provided. From site experience, it has been reported, that under increased load conditions, the TCSC damping function is activated up to several hundred times per day.

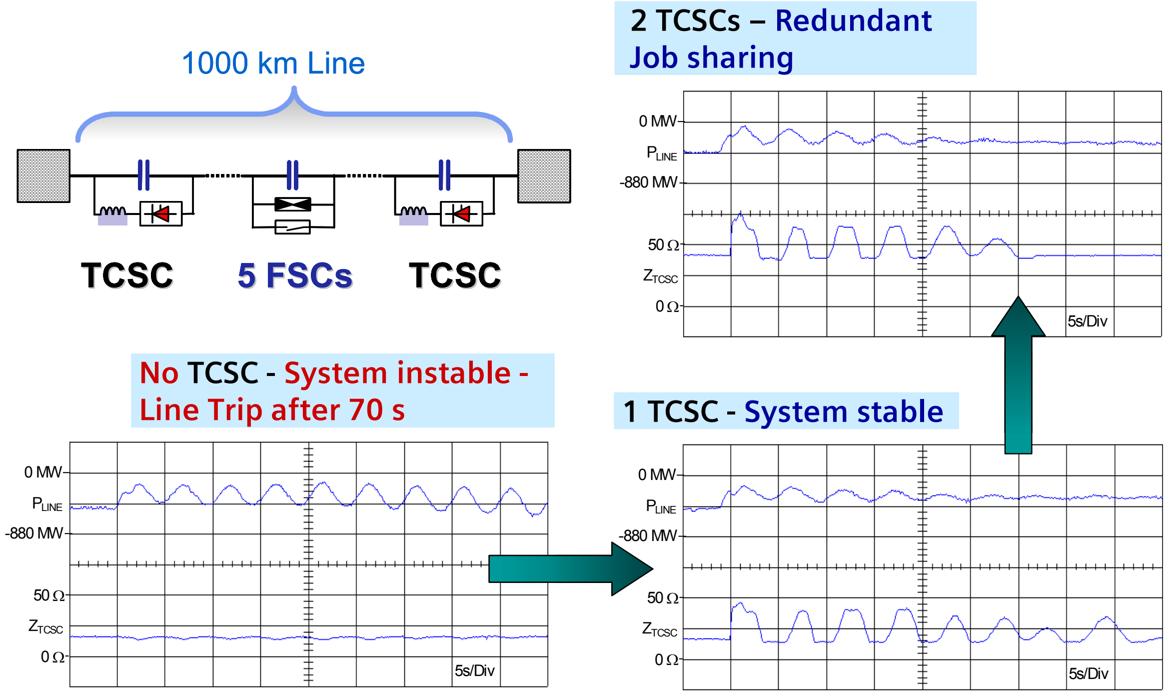
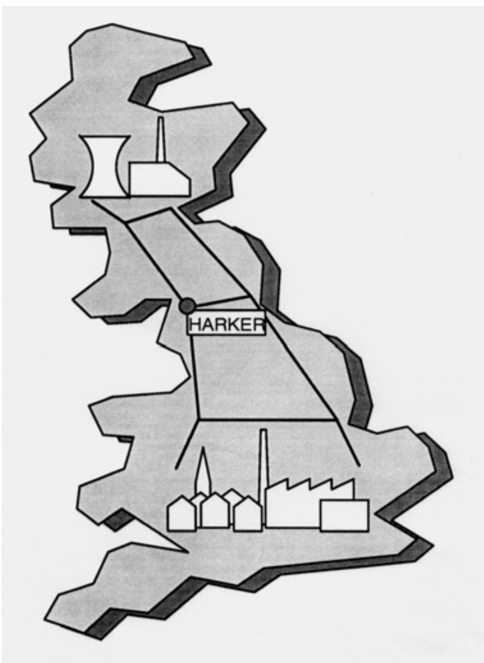


Fig. 11: 500 kV Long Distance AC Transmission in Brazil (Staged-Fault Tests)

In Great Britain, in the course of deregulation, new power stations where installed in the north of the country, remote from the southern load centers (Fig. 12) and some of the existing power stations in the south were shut down due to environmental constraints and for economic reasons. To strengthen the transmission system, a total number of 27 SVC have been installed, because there was no right of way for new lines or higher transmission voltage levels. Fig. 12 gives an example for the two parallel SVC installed in Harker substation, which have been designed mainly for power oscillation damping [7].



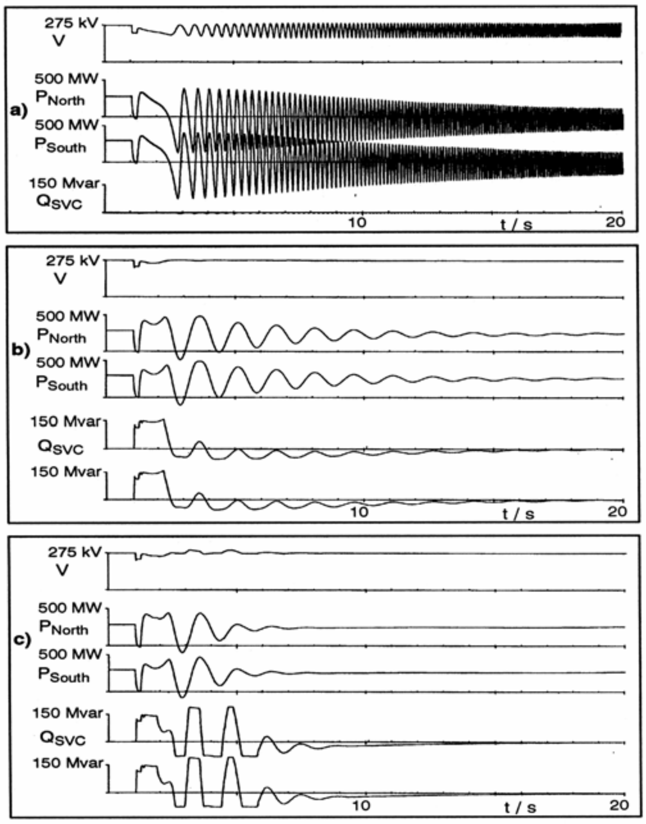


Fig. 12: Strengthening the Transmission System in UK with SVC

In the recordings in Fig. 12 a), no SVC at the critical node in Harker is connected, the system gets unstable after fault application. In Fig 12 b), both SVC are in voltage control mode, the system already achieves stability and in power oscillation damping mode Fig. 12 c), the damping is significantly improved.

Phase Shifting Transformer versus FACTS and HVDC

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. So, 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.

For successful voltage or power flow restoration under transient system conditions, as a thumb rule, 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. Hence, dynamic voltage and load-flow restoration is clearly reserved to power electronic devices like FACTS and HVDC.

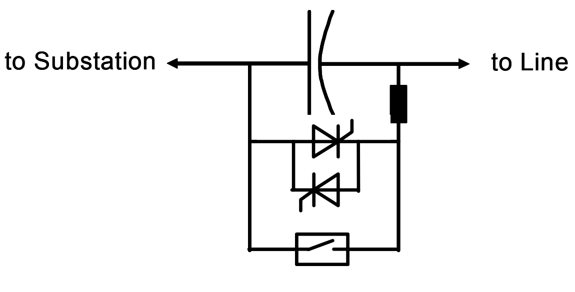
In conclusion, phase shifting transformers and similar devices using mechanical taps can only be applied for very limited tasks with slow requirements under steady state system conditions.

Innovations in FACTS Technology

In series compensation, a capacitor is used to compensate for the lines impedance, thus the line is "virtually" shortened and the transmission angle decreased for system stability improvement. However, during transient conditions, the short-circuit currents cause high voltages across the capacitor, which must be limited to specified values. In the past, this limitation was accomplished by arresters (MOV) in combination with a spark gap.

An AC-fault current flowing through a MOV always leads to a high energy dissipation of the MOV. The MOV heats up heavily. Due to an upper temperature limit the MOV must cool down before the next current stress can be absorbed. Cooling down requires a large amount of time, time constants of several hours are known. 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.

Both the (mechanical) gap function and the MOV can now be replaced by an innovative solution with special high power light-triggered thyristors [8]. These thyristors are designed and tested for a 110 kA peak current capability and they have a very fast cooling-down time. Using this new technology, significant cost savings after system faults can be achieved. Fig. 13 shows the principle of the TPSC and the cost savings for each fault on one of the 3 lines at the 500 kV TPSC installation at Vincent Substation, USA. In case of faults nearby the substations all 3 lines are involved in the fault strategy. Then the savings sum up to 270.000 US$ per event.



Benefits of 90.000 US$ per event on 1 line due to faster available TPSC
e.g. reduction from 1200 MW to 600 MW with FSC/MOV *

*** 25 US$/MWh x 600 MW x 6 hrs**

Fig. 13: Operating Principle of TPSC and Cost-Savings for each System Fault

Fig. 14: Site-View of one of the 3 Vincent TPSC

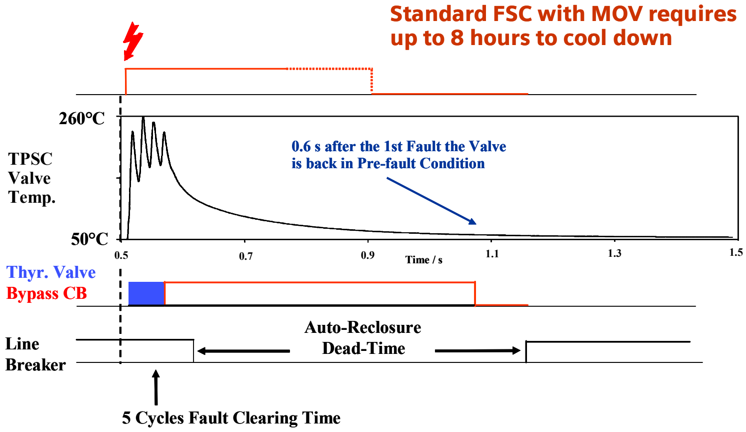


Fig 15: Fast Cooling- Down Time of the High Power Thyristor

Fig. 14 shows a site view of the TPSC and Fig. 15 the fast cooling-down time of the high power thyristor.

Increasing generation in high load density networks on one hand and interconnections among the systems on the other, increases the short-circuit power. If the short-circuit current rating of the equipment in the system is exceeded, the equipment must be upgraded 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, however it reduces the system stability and there is impact on the load-flow.

By combining the TPSC with an external reactor, whose design is determined by the allowed short-circuit current level, this device can also be used very effectively as a short-circuit current limiter (SCCL). This new device operates with zero impedance in steady-state conditions, and in case of a short-circuit it is switched within a few ms to the limiting-reactor impedance.

Fig. 16 shows the basic function and the operating principle of the SCCL. In Fig. 17, a 3-D view of the SCCL is given. In comparison with the TPSC site view in Fig. 14, it can be seen, that the TPSC is just complemented by an additional reactor for the current limitation.

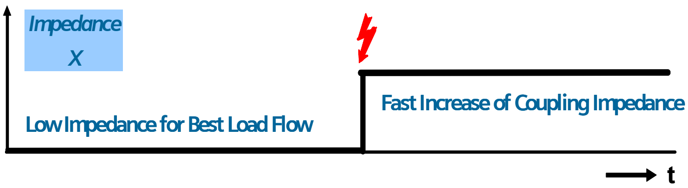
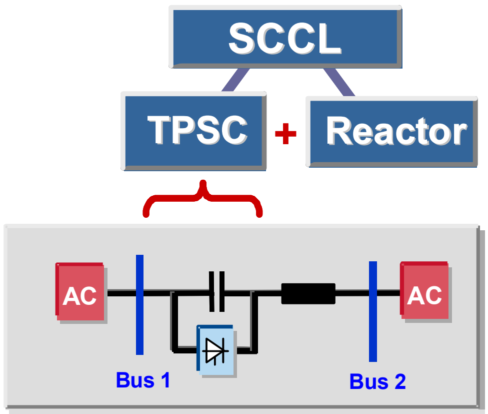


Fig. 16: SCCL - Short-Circuit Current Limitation with TPSC



By means of control add-on functions, both TPSC and SCCL can also be applied for power oscillation damping and for mitigation of subsynchronous resonances (SSR).

In conclusion, with the FACTS based TPSC and SCCL, an innovative break-through in transmission technology for high-voltage systems has been achieved.

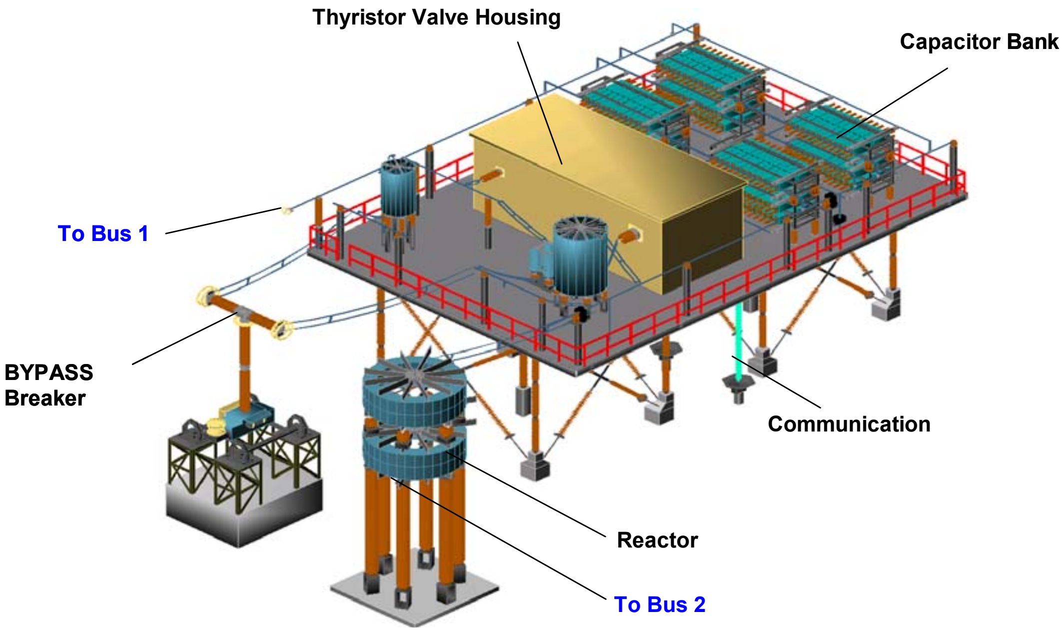


Fig. 17: 3-D View of the SCCL

Summary

FACTS controllers have been developed to improve the performance of long distance AC transmission. Later their use has been extended to load-flow control in meshed and interconnected systems. Typical applications of FACTS in power systems are presented and the benefits for transmission are shown. Excellent on-site operating experience is being reported, and the FACTS technology became mature and reliable.

In the paper, features of the different FACTS Controllers are explained and the market aspects are discussed. Comparison with conventional, mechanical equipment like Phase Shifting Transformers is given.

Highlights of innovative FACTS technologies are presented and their benefits for new applications are demonstrated.

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