

BENEFITS OF FACTS FOR LARGE POWER SYSTEMS

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0. Abstract

The performance of power systems decrease with the size 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 deregulation of the electrical power markets, where contractual power flows do not follow the design criteria of the existing network configuration. Additional problems can arise in case of interconnections, especially when the connecting AC links are weak.

Dynamic problems can occur which endanger the reliability of the synchronous operation. If power should be transmitted through the interconnected system over longer distances, transmission needs to be supported. This is for example the case in the West-European UCTE system, where the 400 kV voltage level is relatively 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.

Keywords:

Development of Power Systems - Power System Interconnection - FACTS Technology -
System Stability - Transmission Efficiency

1. Introduction

The development of electric power industry follows closely the increase of the demand on electrical energy. Main driving factors for energy consumption, valid nowadays, 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 only about 1 to 2 % per year with the expected doubling of the demand in 30 to 50 years.

In the next 20 years, power consumption in developing and emerging countries is expected to grow for 220 %, in industrialized countries, however, only for 37 %. It means that further development of power systems can be expected mainly in the areas of developing and emerging countries.

The importance of gas as energy source will further increase, the relative importance of coal, oil and nuclear power will decrease. The regenerative energy sources without hydro are expected to increase fast, however, in total they will be still only in the range of about 4 %.

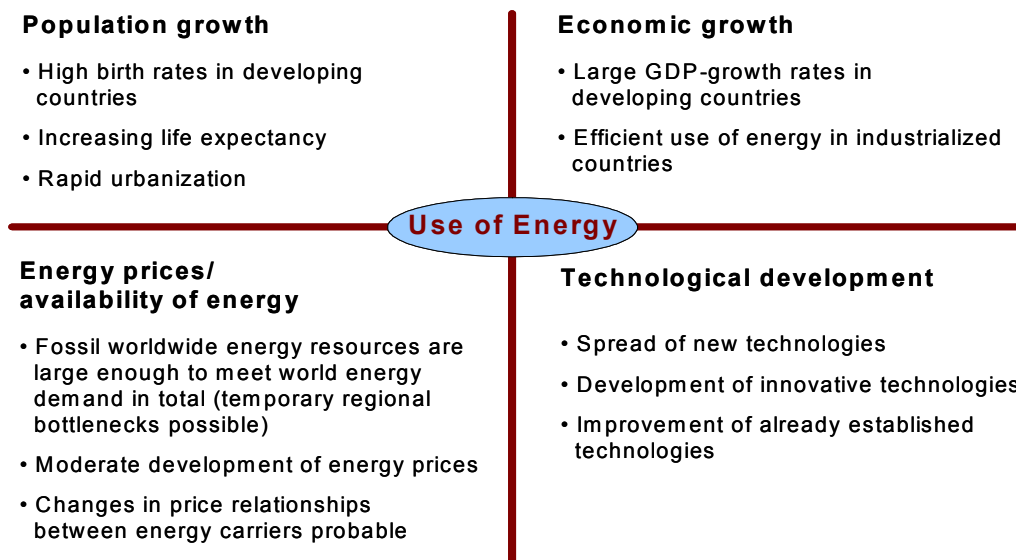


Fig. 1: Main driving factors for energy consumption

2. Development of Transmission Systems

The development of transmission systems follows the task to transmit power from generation to consumers. With an increased demand on energy and the construction of large generation plants built at locations remote from load centers, power needs to be transmitted over long transmission distances. The AC transmissions designed for large power transfers and consequently for high operating voltages became a technically extremely challenging subject because of severe voltage, reactive power and stability problems. However, for large power blocks transmitted over long distances, the HVDC Transmission became an important technical alternative. A further possibility to improve the power system performance for transmission over long distances is the use of FACTS (Flexible AC Transmission Systems) [1, 2], based on power electronics.

During their development, power systems have grown first to regional, then to national and finally to large internationally interconnected networks using high voltage levels. The goal for power industry to establish electricity supply arrangements with the neighboring partners is a major stimulation towards the extension to interconnected systems. The operating voltage of such interconnected systems depends mainly on geographic conditions and the average transmission distance to transmit power. Fig. 2 shows the historical development of voltage levels for AC power systems.

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 has been anticipated in the past in some countries and also some test lines have already been built. However, it is not expected in the near future that this voltage level will be utilized to a larger extent.

Based on studies of power system developments in different world regions expectations for future trends are listed in Fig. 3.

The integration of electric power systems into large interconnected systems is based on benefits regarding energy costs, supply reliability, provision of reserve generation etc. During time, however, the interconnected systems take over also the task to transmit power through the network over larger distances. This is particular the case in the liberalized environment, where customers can buy energy from the cheapest seller which could be far away, and the power system operator has to provide a technically reliable transmission to fulfill such contracts.

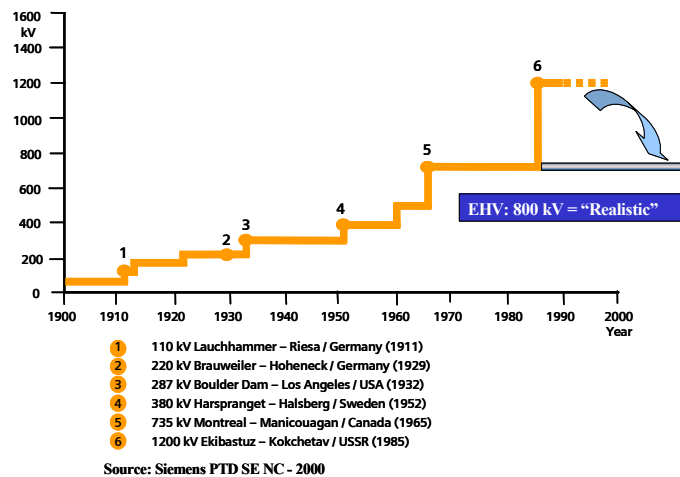


Fig. 2: Development of AC-Voltage Levels - Milestones

Next step in the interconnections is the integration of national or regional interconnected systems to very large networks which could cover parts of or even whole continents.

The final possible step in this development is a global network, which would be gradually built, interconnecting also continents. The driving factor for such a network could be the utilization of huge potential of renewable power resources worldwide, mainly due to ecological requirements.

However, in large interconnected and long distance transmission systems technical problems can be expected [3-5], which are summarized in Fig. 4. In the interconnected networks mainly problems regarding load flow, system oscillations and inter-area oscillation occur. If systems have large extension and have to transmit large power over long distance, additional voltage and stability problems can arise.

Fig. 4: Technical Problems in AC systems

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

In the next sections, means are shown how to solve these system problems.

3. FACTS

Fig. 5 gives an overview of today's FACTS devices and their ability for system performance improvement. Flexible AC Transmission Systems (FACTS), based on power electronics, have been developed to improve the performance of weak AC Systems and for long distance AC transmission [2]. Excellent operating experiences are available worldwide and the technology became mature and reliable.

FACTS can, however, contribute to solve also technical problems in the interconnected power systems. Examples will be discussed showing how FACTS can improve synchronous operation of the interconnections and influence load flow conditions. Fig. 5 summarizes the impact of FACTS on system performance when using different devices. Evaluation is based

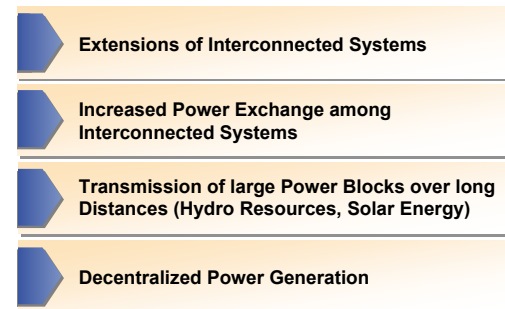


Fig. 3: Development of Power Systems

on a large number of studies and experiences from realized projects. In the same figure, for comparison, also properties of HVDC are listed.

Principle	FACTS	Scheme	Impact on System Performance		
			Load-Flow	Stability	Voltage Quality
Variation of the Line Impedance: Series Compensation	FSC (Fixed Series Compensation)		●	● ● ●	●
	TPSC (Thyristor 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)		● ● ●	● ●	● ●
	UPFC (Unified Power Flow Controller)		● ● ●	● ● ●	● ● ●

Influence:

- low or no
- small
- ● medium
- ● ● strong

Fig. 5: FACTS – Overview and Functions

Main FACTS applications are Static Var Compensators (SVC), providing fast voltage control, reactive power control and power oscillation damping features. As an option, SVC can also control system unbalances. A view of an SVC installation in Great-Britain and a typical single-line diagram is given in Fig. 6. Static Var Compensators are connected via transformers to the high-voltage system in order to achieve an economical thyristor design.

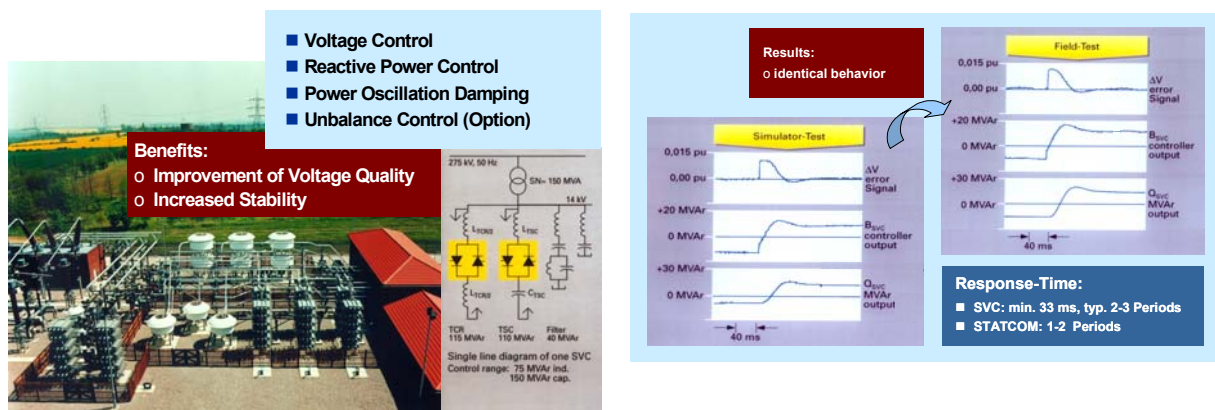


Fig. 6: SVC – Site View, Control Functions and Single-Line Diagram

Fig. 7: SVC - Response Time Measurements (Simulator and On-Site)

An example of a response-time measurement for SVC in voltage control mode (on-site and simulator recordings) is given in Fig. 7.

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 for load-

flow control, and it is very effective also for power oscillation damping. Special FACTS controllers are STATCOM (Static Synchronous Compensator, with self-commutated devices such as GTO, IGBT or IGCT) and UPFC (Unified Power Flow Controller), which uses coupled parallel and series converter branches [1, 2]. The response time of STATCOM is faster than that of SVC. However, for most applications in transmission systems and interconnections, SVC, TCSC and FSC are used fulfilling normal requirements of the grid. STATCOM and UPFC are tailored solutions for special needs.

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, ref. to section 5.

A large number of different FACTS devices have been put into the operation either as commercial projects or prototypes. The market expectations for FACTS and additionally also for HVDC are presented in Fig. 8.

Static Var Compensation (SVC) is mainly used to control the system voltage. 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. The market for FACTS equipment applied for load flow control is expected to develop faster in the future, also as a result of the liberalization in power industry. TCSC has already been used in different projects for load flow control, stability improvement and to damp oscillations in interconnected systems. The market in the HVDC field, however, is further progressing fast. A number of large long distance transmission schemes using either overhead lines or submarine cables and back-to-back (B2B) projects have been put into operation or are in the stage of installation.

Shunt Compensation	SVC	• • •
	STATCOM	•
Series Compensation	FSC	• • •
	TCSC	• •
Combined Device	UPFC	•
Power Transmission	HVDC	• • •

• • • Excellent Market
 • • Upcoming Market
 • Small Market

Fig. 8: Market of FACTS and HVDC

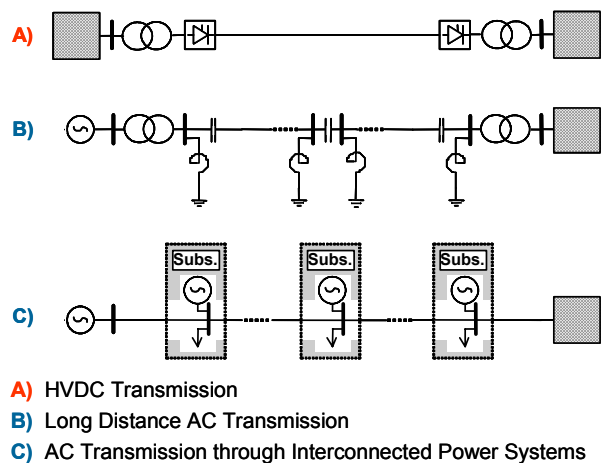
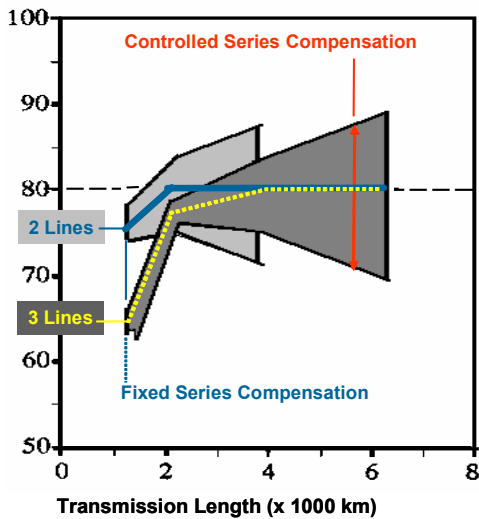


Fig. 9: Network Configurations for Long Distance Transmission

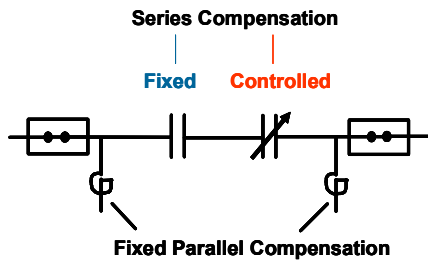
4. Use of FACTS in Transmission and Interconnected Systems

There are different possible solutions to transmit power over long distances, depending on the system configuration, transmission distance and the use of transmission technology. Fig. 9 shows the three alternatives: a) HVDC transmission, b) HVAC transmission using strong reactive power compensation and c) the transmission of power through the interconnected systems.

Degree of Series Compensation



Example: 765 kV Transmission



Source: Siemens PTD SE NC - 2002

Fig. 10: Limits of long distance AC transmission

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. 10 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 parallel 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. 11 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.

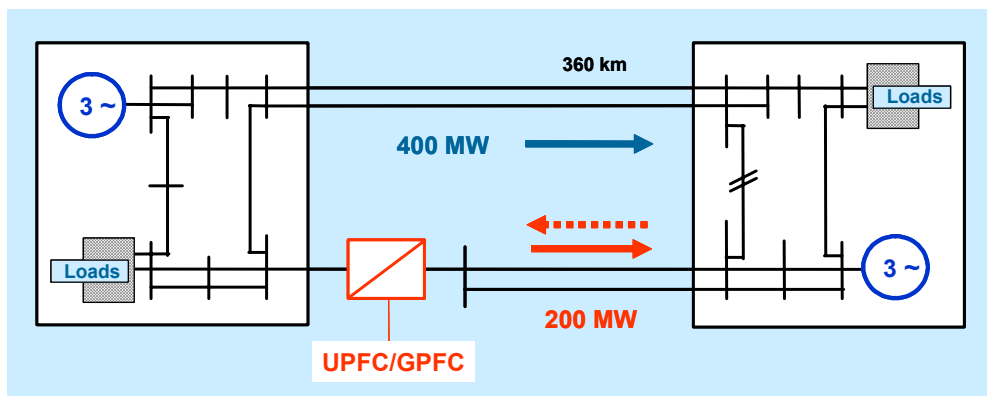


Fig. 11: Avoidance of Loop-Flows with FACTS Power Flow Controller

In case that power should be transmitted through a meshed system, undesired load flow occurs 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. 12 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 through the neighboring systems. Only a limited amount of power is flowing directly to the target location. Using a FACTS controller, however, load flow can be significantly improved.

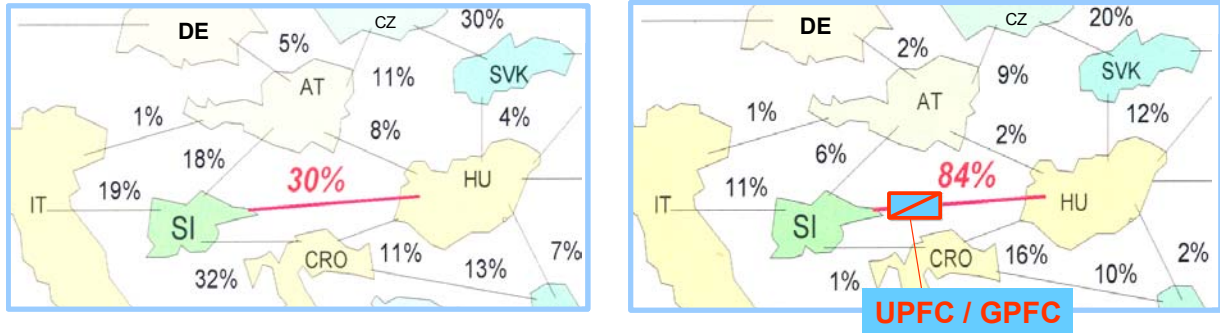


Fig. 12: UCTE: Load Flow Improvement by means of FACTS

In Fig. 13, 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 or HVDC [3] would be necessary for maintaining the stability after disturbances.

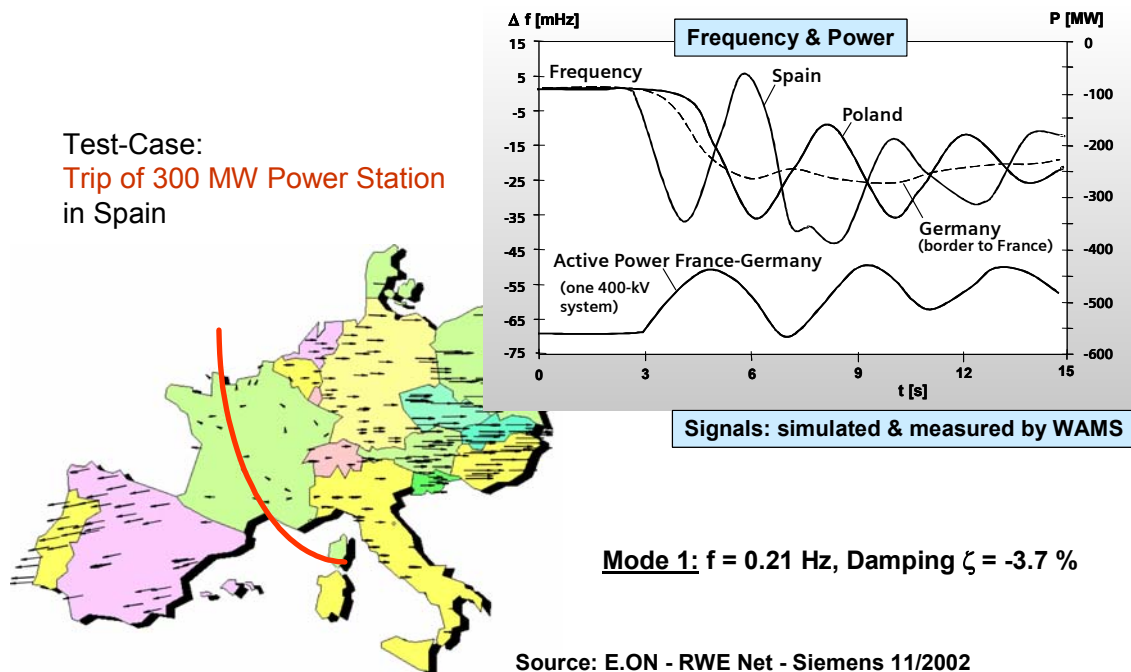


Fig. 13: Interarea-Oscillations in UCTE

In Fig.14 it is shown, how such problems with inter-area oscillations are solved in the Brazilian System. There, the situation is even more critical because of a very long transmission distance between the interconnected systems: a 500 kV long distance AC interconnection between North and South systems has been realized. In the interconnection two TCSC devices have been installed at both ends of the interconnection which damp the inherent oscillations that occur between the systems. 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.

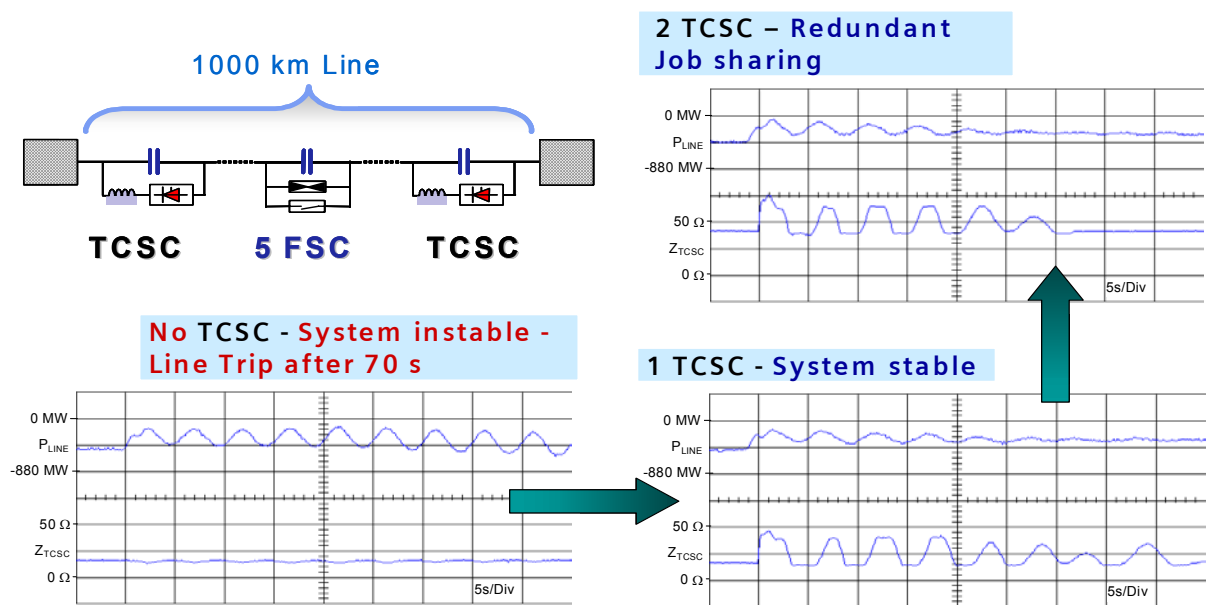


Fig. 14: 500 kV Long Distance AC Transmission in Brazil (Staged-Fault Tests)

In Great Britain, in the course of deregulation, new power stations were installed in the north of the country, remote from the southern load centers (Fig. 15) 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. 15 gives an example for the two parallel SVC installed in Harker substation, which have been designed mainly for power oscillation damping [7].

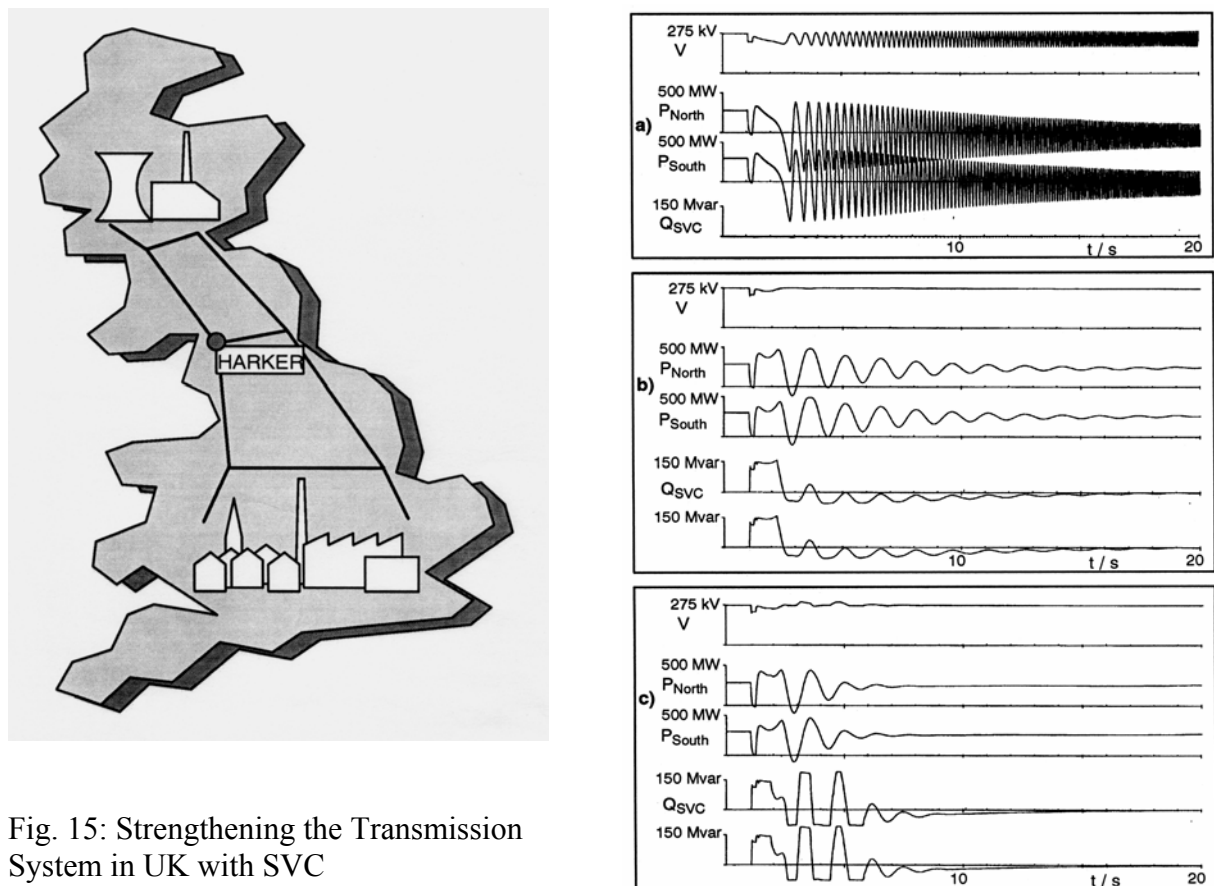


Fig. 15: Strengthening the Transmission System in UK with SVC

In the recordings Fig. 15 a), no SVC at the critical node in Harker is connected, the system gets unstable after fault application. In Fig 15 b), both SVC are in voltage control mode, the system already achieves stability and in power oscillation damping mode Fig. 15 c), the damping is significantly improved.

5. 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. 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. 16 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 [8]. 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. Fig. 17 shows the site view and Fig. 18 the fast cooling-down time of the thyristor.

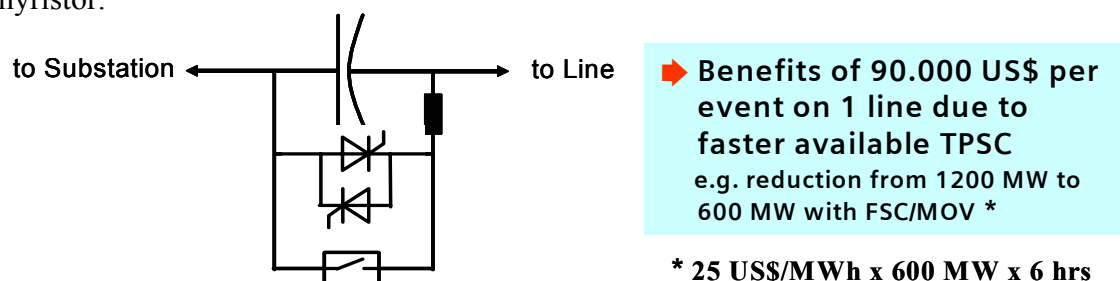


Fig. 16: Operating Principle of TPSC and Cost-Savings for each System Fault



Fig. 17: Site-View of one of the 3 Vincent TPSC

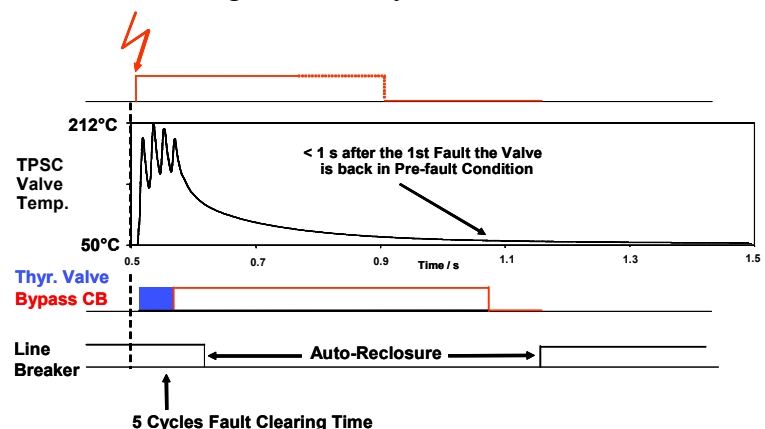


Fig. 18: Fast Cooling-Down Time of the High Power Thyristor

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 as a short-circuit current limiter (SCCL). Fig. 19 shows the basic function and the operating principle of the SCCL.

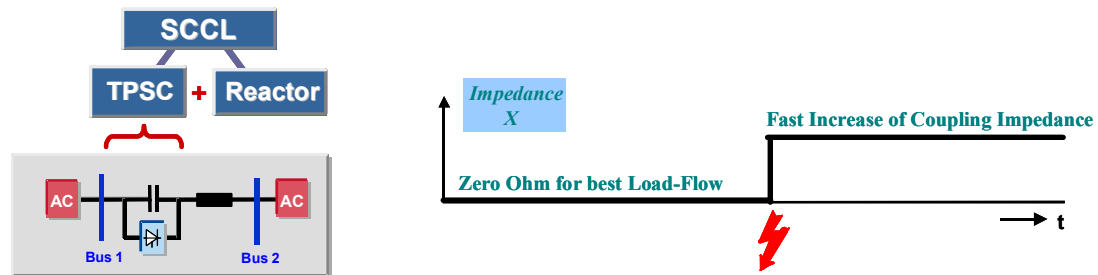


Fig. 19: SCCL – Short-Circuit Current Limitation with TPSC

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 TPSC and SCCL, an innovative break-through in transmission technology for high-voltage systems has been achieved.

6. Summary

FACTS controllers have been developed to improve the performance of weak systems and long distance AC transmission. Innovations in FACTS developments are presented and the benefits for power transmission are explained. Excellent on-site operating experience is being reported, and the FACTS technology became mature and reliable.

In the paper, examples of FACTS Controllers and their applications are presented and the improvements of the transmission system are discussed. Discussion is focused on the use of FACTS for large system interconnections.

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