FACTS DEVICES APPLICATION FOR POWER QUALITY IMPROVEMENT

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INTRODUCTION

Electric power system is in transition state from regulated, vertical structure into deregulated, more market oriented structure. Both transmission and distribution system must be adapted to new circumstances. Application of modern technologies based on static switching devices, sophisticated control algorithms and usage of digital microprocessor technologies in electric power system operation has been forseen as a way for improving the system by researches and experts all over the World.

Worldwide transmission systems are becoming more heavily loaded and are being operated in ways not originally planed. It is expected that they become flexible to react to more diverse generation and load patterns. Further more, the economical utilization of transmission system assets is of great importance for market oriented power system both for industrial countries, to remain competitive and to survive and for developing countries, to optimized use of transmission systems investments, to support industry, create employment and utilize efficiently scarce economic resources.

At distribution level the focus is in delivering good power quality to the customers. Last decade has seen a market increase in loads that are sensitive to poor quality of electricity supply. Some large industrial users are critically dependent on uninterrupted electrical supply and suffer large financial losses as a result of even minor lapses in the quality of electrical supply. Additionally, distributed generation and cogeneration units are added to distribution network in order to fulfill growing needs for energy and to enable more stable operation of the system.

Power electronic based equipment is the most promising technology that can, and already is, able to respond to new operating challenges. Advancements of these devices are based on high performance and rapid response capability. For transmission systems, power electronic based equipment provide strategic benefits for improved management through better utilization of existing transmission assets, increased transmission system reliability and availability, increased dynamic and transient grid stability, increased quality of supply, etc. Such systems are known as **F**lexible **AC T**ransmission **S**ystems (FACTS). Major development in distribution sector is the incorporation of power electronic devices in these systems to supply selected customers with high quality power. The generic, systematic solution being considered by the utility to counter the problem of interruptions and low power quality at the end-users level is known as Unified Power Quality Conditioning Systems (UPQCS) or Custom Power. Moreover, power electronic device enable connection of new renewable energy sources, such as wind and solar power plants, into the distribution network and their efficient usage (1).

In this paper the focus will be on application of FACTS devices for improving existing performances, increasing the reliability and dynamic stability of the system and for better of power quality. An overview of the modern solutions of FACTS devices is given, together with a survey of some FACTS installation all over the World.

FACTS DEVICES CLASSIFICATION

There are different ways of FACTS classification in literature, depending on their different characteristics, technology, connection etc.

In (2) a multi-dimensional classification scheme is suggested. FACTS devices are classified according to five independent parameters: connection; commutation; switching frequency; energy storage and dc port. Beside some drawbacks, suggested classification has some advantages. First of all one type of FACTS device is designated with unique “name”, which prevent confusion. Such scheme is convenient to researchers wishing to develop new techniques, as it is relatively simple to find out, which characteristic combination is not developed. According to (2) there are 23 different types of FACTS devices.

The IEEE, groups FACTS controllers by way they are connected to the AC power system into three main categories (3): series, shunt, and combined series-and-shunt (FACTS devices modify the series and parallel impedances of transmission lines). The way a FACTS device is connected to the AC power system has a direct effect on the transfer of active and reactive power within the system. Series connected devices are usually employed in active power control and to improve the transient stability of power systems. Shunt connected devices govern reactive power and improve the dynamic stability.

In (4) FACTS devices are compared with conventional solutions for the problem in transmission network, thus making a classification more connected to the real situation in the field. Table 1 presents such approach giving information concerning problem, correction action, conventional and FACTS device solution correction action.

In (5), the term ‘FACTS’ is defined as all of the power electronics based systems used in AC power transmission. The main systems are distinguished as families of devices:

- Static VAr compensator (SVC)
- Series compensation devices
- Phase-shifting devices
- Synchronous static devices compensator (STATCOM)
- Unified power flow controller (UPFC)

Then, each of the family is further specified according to particular devices. The Static VAr compensators include following devices: Thyristor-controlled reactor (TCR), Thyristor-switched capacitor (TSC), Thyristor-switched reactor (TSR) and Mechanically switched capacitor (MSC). Series compensation is obtained with fixed series capacitor and thyristor-controlled series capacitor (TCSC). Phase-shifting devices consist of Phase-shifting transformer (PST) and Assisted phase-shifting transformer (APST). Synchronous static devices are Synchronous static compensator (STATCOM) and Synchronous static series compensator (SSSC). Unified power flow controller is complex device consisting of two or more power converter.

There are other possibilities for FACTS classification, as this field is still in constant developing stage, but this paper will limit itself to only the most promising realizations.

THE MOST IMPORTANT FACTS DEVICES

Some of above-mentioned FACTS devices have already find their way to practical implementation and distinguished themselves from the others. Such devices are considered as the most important or the main types of FACTS ones and will be described in more details.

Static VAR Compensator (SVC)

At this point of view SVCs are most widely installed types of FACTS. From operation point of view, the SVC (Figure 1) behaves as shunt connected variable reactance, which either generate or absorb reactive power in order to regulate the voltage magnitude at the point of connection to the AC network (1). It is used to provide fast reactive power and voltage regulation support. It is also known to increase system stability margin and to damp power system oscillation. Figure 1a shows most typical arrangement of SVC with fixed capacitor (FC) and TCR. Figure 1b shows SVC realized with TCR and TSC.

Table 1 - FACTS device classification according to corrective action (4).

Issue	Problem	Corrective Action	Conventional solution	FACTS device*
Voltage limits	Low voltage at heavy load	Supply reactive power	Shunt capacitor, Series capacitor	SVC, TCSC, STATCOM
	High voltage at light load	Remove reactive power supply	Switch EHV line and/or shunt capacitor	SVC, TCSC, STATCOM
		Absorb reactive power	Switch shunt capacitor, shunt reactor	SVC, STATCOM
	High voltage following outage	Absorb reactive power	Add shunt reactor	SVC, STATCOM
		Protect equipment	Add arrestor	SVC
	Low voltage following outage	Supply reactive power	Switch shunt capacitor, reactor, series capacitor	SVC, STATCOM
		Prevent overload	Series reactor, PAR	TCPAR, TCSC
	Low voltage and overload	Supply reactive power and limit overload	Combination of two or more devices	TCSC, UPFC, STATCOM, SVC
Thermal limits	Line or transformer overload	Reduce overload	Add line or transformer	TCSC, UPFC, TCPAR
			Add series reactor	SVC, TCSC
	Tripping of parallel circuit (line)	Limit circuit (line) loading	Add series reactor, capacitor	UPFC, TCSC
Loop flows	Parallel line load sharing	Adjust series reactance	Add series capacitor/reactor	UPFC, TCSC
		Adjust phase angle	Add PAR	TCPAR, UPFC
	Post-fault sharing	Rearrange network or use “Thermal limit” actions	PAR, Series Capacitor/Reactor	TCSC, UPFC, SVC,
	Flow direction reversal	Adjust phase angle	PAR	TCPAR, UPFC
Short circuit levels	Excessive breaker fault current	Limit short circuit current	Add series reactor, new circuit breaker	SCCL, UPFC, TCSC
		Change circuit breaker	Add new circuit breaker	
		Rearrange network	Split bus	
Sub synchronous resonance	Potential turbine /generator shaft damage	Mitigate oscillations	Series compensation	NGH, TCSC

* Legend for the Table 1 is given in appendix.

Thyristor Controlled Series Capacitor (TCSC)

The TCSC varies the electrical length of the compensated transmission line with little delay (1). Because of this characteristic, it may be used to provide fast active power flow regulation. It also increases the stability margin of the system and has proved very effective in damping sub-synchronous resonance and power oscillations.

Basic TCSC, depicted in Figure 2, is formed with TCR placed in parallel with capacitor. The controlling elements in TCSCs are two back-to-back thyristors, connected in series with reactor. TCSC can work in three operation modes:

- thyristor blocked mode (current through TCR are zero and TCSC operates as a capacitive reactance);
- thyristor bypassed mode (thyristor operates at full conduction angle and TCSC have small reactive impedance);
- thyristor operating in phase controlled mode (value of the firing angle determines direction of the current through TCR and capacitor, enabling the TCSC to work as either a capacitive or an

inductive reactance. In this mode the thyristor firing mechanism is controlled to vary the amount of effective reactance connected to the system. Also, series capacitive compensation is bypassed during low loading to avoid over voltages).

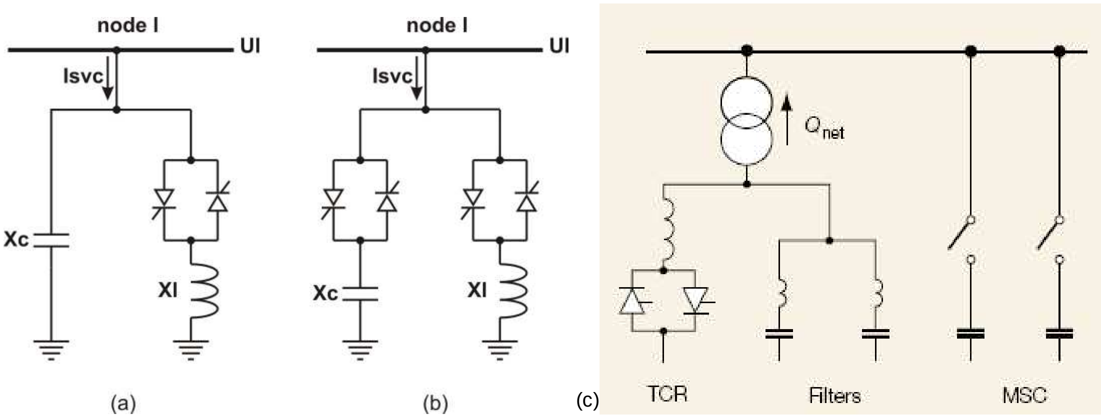

Figure 1 - SCV formed by: (a) capacitor and TCR, (b) with combination of TCS and TSR and (c) combination of TCR, passive filters and MSC (1,5).

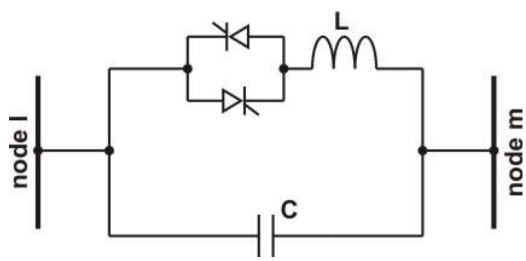

Figure 2 - TCSC formed by capacitor and TCR

Static Compensator (STATCOM)

STATCOM (Figure 3a) can be defined as fast responding generators of reactive power with leading or legging reactive energy capability. It can provide steady state reactive power compensation as well as dynamic compensation during power system transients. STATCOM's are employed at distribution and transmission levels. When a STATCOM is employed at distribution level or at the load end for power factor improvement and voltage regulation it is called DSTATCOM.

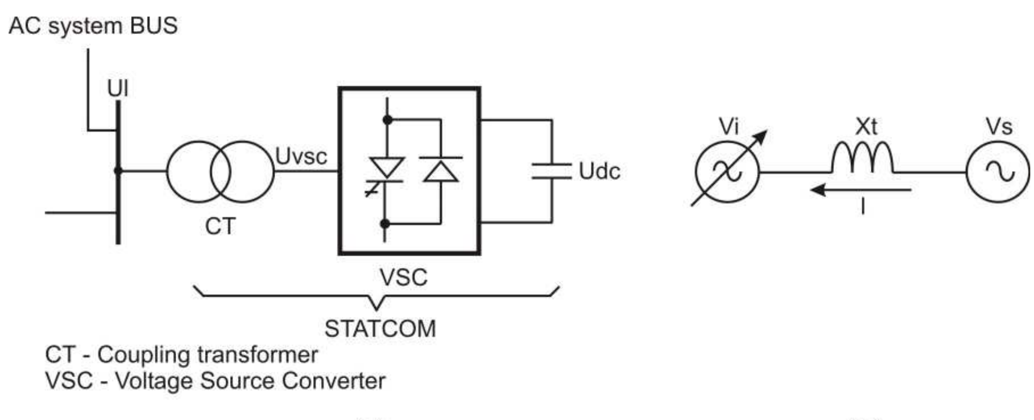

Figure 3 – The STATCOM device (a) and STACOM equivalent circuit (b)

Principle of work is based on relation between STATCOM's VSC converter output voltage (Vi) and system voltage (Vs). If Vi is equal to Vs, than no reactive power is deliver to the power system. If Vi is higher than Vs (Figure 3b), the phase angle of I is leading with respect to phase angle of Vs by 90 degrees and leading reactive power flows from STATCOM to power system (capacitive mode). In other case, when Vi is lower then Vs, phase angle of I, regarding phase angle of Vs, is legging by 90 degrees and legging reactive power flows from system to STATCOM (inductive mode). Compared to SVC, STATCOM have many advantages such as (6,7):

- quicker response time;
- active power control is possible (with optional energy storage on DC circuit);
- no potential for creating a resonance point;
- smaller installation space and
- modular design allows high availability (i.e. one or more modules can be out of service without of loss of the entire compensation system).

Dynamic Voltage Restorer (DVR)

The DVR (Figure 4) is a series connected VSC. It can scientifically contribute to increase voltage circumstance in low voltage distribution applications where problems with voltage swells and sags are typical. It injects voltage in quadrature with one of the line end voltages in order to regulate active power flow. Because it has its own source of reactive energy it can also regulate reactive energy flow. Because of such attributes, DVR is capable to regulate both reactive and active power flow. It may perform a role of series phase shifter and a variable series impedance compensator.

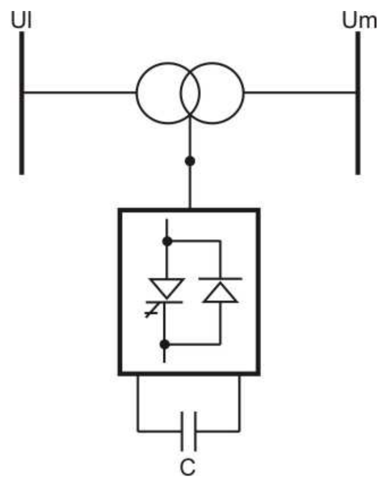

Figure 4 – The Dynamic Voltage Restorer (DVR)

Unified Power Flow Controller (UPFC)

The UPFC can be described as device that consists of STATCOM and DVR that share same DC bus and unified control system. The UPFC allows simultaneous control of active power flow, reactive power flow and voltage magnitude at the UPFC terminals (1).

Reactive power, controlled by series converter, is drawn from system by shunt converter. DC bus voltage is inverted and added to system voltage at node where series converter is connected to system. In addition to providing a supporting role in the active power exchange that takes place between the series converter and system, the shunt converter may also generate or absorb reactive power in order to provide independent voltage magnitude regulation at its point of connection.

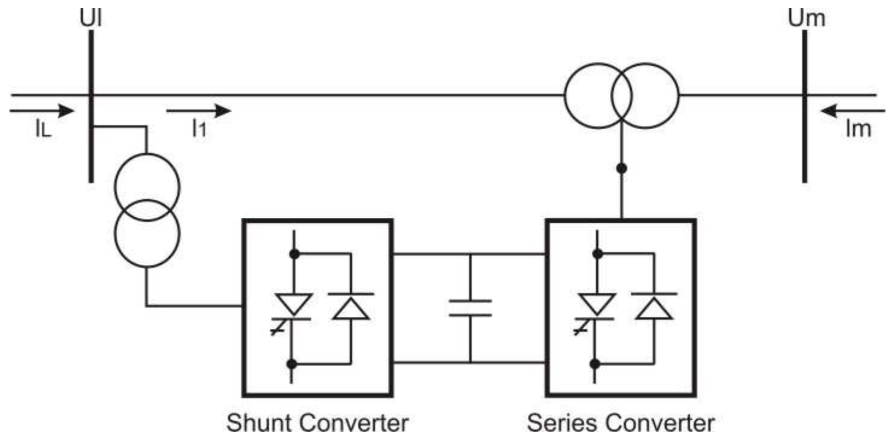

Figure 5 - The Unified Power Factor Controller (UPFC)

FACT DEVICE APPLICATION

Here will be presented details of some major examples of FACTS devices that are presently in service (5,8,9).

SVC installation at Sylling, Norway

An example of an installation in a meshed network is the SVC at Sylling, near the city of Oslo in southern Norway (Figure 6). This plant is rated at ± 160 MVAr and is connected to the 420-kV system at a substation south-west of the city. If a short circuit occurs in the network, the SVC detects the resulting voltage depression on the 420-kV system and changes its impedance to quickly restore the voltage in the city. As a result of the fault the generators in the system also start to increase their reactive power output to restore the voltage at the machine locations. The SVC makes sure that this is done smoothly, with the result that the short circuit is not noticed in the city. During fault clearing an overvoltage often occurs as a result of the exciter action. The SVC counteracts this surge. Due to the SVC action during and after the fault, the voltage change is virtually unnoticeable at the load sites in the city. Thus, it can be said that the SVC isolates the city from the effect of the remote system fault.

Figure 6 – The *420-kV SVC installation at Sylling, Norway*

TCSC at Imperatriz, Brazil

TCSC at Imperatriz, Brazil is a part of AC interconnection of two main power systems in the country – the North System and the South System. They transmit mainly hydropower, carrying more than 95 % of the nation's total generated electrical energy. Interconnection consists of a single 500-kV compact circuit, more than 1,000 km long and series-compensated at several locations along the line. The TCSC is located at the Imperatriz substation at the northern end of the interconnection. Its task is to damp low-frequency, inter-area power oscillations between the power systems on either side of the interconnection. These oscillations (0.2 Hz) would otherwise constitute a hazard to power system stability. The boost level is a key factor, being a measure of the amount by which the reactance of the series capacitor can be artificially augmented in order to counteract system power oscillations. The boost level can be varied continuously between 1 and 3, which is equivalent to a range of 5% to 15 %

of the line compensation. At rated line current, the nominal boost level has been set to 1,2. The control scheme and a view to TCSC are shown in Figure 7. The thyristor valve is mounted at platform level (Figure 7-right). It is water-cooled and utilizes indirect light-triggered thyristors rated at 1,500 A.

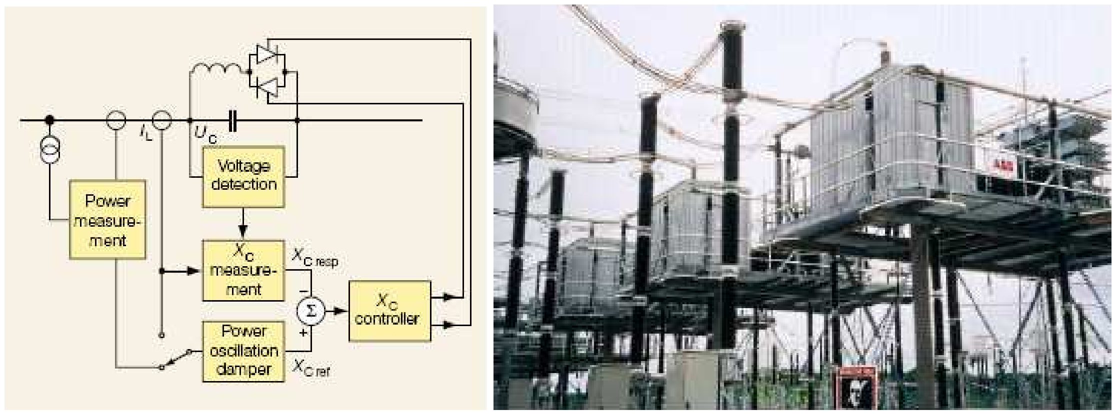

Figure 7 - *Imperatriz TCSC substation: Control scheme (left) and view of the Imperatriz TCSC (right)*

Another example is the Kayenta TCSC installation, commissioned in 1993, consists of two series capacitor banks; each rated 165 MVAr and 1000 Amps with a single phase 60 Hz and impedance of 55 Ohms. One bank is operated in a conventional series compensation configuration with the second bank subdivided into a 40-ohm conventional segment and a 15-ohm TCSC segment. Kayenta substation is in the middle of a 320 km 230 kV transmission line. With power transfers on the interconnected network approaching the transmission system's ability to reliably serve increasing loads, and with restrictions in building new transmission lines series compensation became an attractive alternative to increase power transfer capability. Adding of 330 MVAr of series compensation to the line provides 70% series compensation and increased the power scheduling capability by 30 % to 400 MW.

STATCOM at Sullivan Substation, Tennessee, USA

A ±100Mvar static synchronous compensator (STATCOM) at the Sullivan substation in the TVA (Tennessee Valley Authority) power system has been in operation from 1995. Installation consisted of the following major pieces of equipment: 48-pulse, two-level voltage source inverter that combines eight, six-pulse three-phase inverter bridges, each with a nominal rating of 12.5MVA; a single step-down transformer having a wye and delta secondary to couple the inverter to the 161kV transmission line; a closed-loop liquid cooling system that contains a pumping skid and a fan-cooled, liquid-to air heat exchanger unit; and a central control system with operator interface.

The STATCOM regulates the 161kV bus voltage during daily load increases to minimize the activation of the tap changing mechanism on the transformer bank, which interconnects the two power systems. The use of the STATCOM to regulate the bus voltage has resulted in reduction of the use tap changer from about 250 times per month to 2 to 5 times per month. Tap changing mechanisms are prone to failure, and the estimated cost of each failure is about $1M. The Sullivan substation is also equipped with a mechanically switched 84Mvar capacitor banks to extend the effective range of the STATCOM to 184Mvar capacitive to 100Mvar inductive. This bank is directly controlled by the STATCOM on a contingency basis in the event that the Sullivan transformer bank is lost during winter peak conditions. If this occurs, a 10 to 15 percent drop in the 161 kV bus voltages will result. The rapid and coordinated control of the STATCOM with the fixed capacitor bank will eliminate this problem by maintaining the voltage at reasonable levels until shunt capacitor banks at other substations in the general area can be energized. Without the STATCOM, TVA would be compelled either to install a second transformer bank at Sullivan or to construct a fifth 161 kV line into the area; both are costly alternatives. The STATCOM has allowed TVA to defer these large expenditures.

UPFC at Inez Substation, Kentucky, USA

The first UPFC at the American Electric Power, Inez substation, was commissioned in 1998. The Inez load area has a power demand of approximately 2000 MW and is served by long heavily loaded 138 kV transmission lines. During normal power delivery, there is a very small voltage stability margin for system contingencies, which could result in a wide-area blackout. A reliable power supply to the Inez area, therefore, requires effective voltage support and added real power supply facilities.

Among other things (erection of a new double-circuit high-capacity 138 kV transmission line), an installation of a FACTS controller to provide dynamic voltage support at the Inez substation and to ensure full utilization of the new high capacity transmission line, have been projected. The UPFC satisfies all these needs, providing independent dynamic control of transmission voltage as well as real and reactive power flow.

The UPFC installation (Figure 8) comprises of two identical, three-level 48-pulse, 160 MVA voltage source inverters coupled to two sets of dc capacitor banks two "intermediate" transformers, two identical step-down shunt transformers and a single series transformer. The transformers are connected to the inverters through bus-work and manually operated disconnect switches.

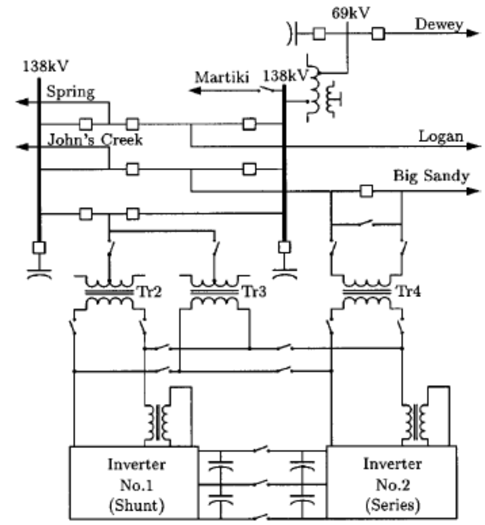

Figure 8 - 160-MVA UPFC installation at Inez.

Expected benefits of the Installed UPFC are seen to be: dynamic support of voltage at the Inez substation to prevent voltage collapse under double transmission contingency conditions; flexible, independent control of real and reactive power flow on the new high capacity (950 MVA thermal rating) Big Sandy to Inez 138 kV transmission line; optimal utilization of the existing transmission system; frees up transmission capacity for years of load growth; reduction of real power losses by more than 24 MW, which is equivalent to a reduction of CO2 emissions by about 85,000 tons per year. The quantified impact of the UPFC on power transfer and power quality at the Inez substation is more than 100 MW increase in the power transfer and excellent voltage support at the Inez bus.

CONCLUSION

Deregulation and the opening of electricity networks to facilitate competition will led to changes in power flow patterns in transmission networks, previously planned. It has also led to much uncertainty in the way markets for new generation and customers will evolve making planning of transmission networks more difficult. Measures such as relocatability of transmission plant are meant to address this aspect. However another important measure is system flexibility and an ability to control or channel flows so as to make maximum use of existing networks. Building new lines against uncertain future transmission needs is difficult particularly in view of environmental concerns.

FACTS devices do not provide new transmission capacity, but remove constraints and enable improved use of existing transmission networks. They are capable of fast control and result in improved power quality, too. Where new lines are not an option their application must be compared with conventional methods e.g. network rearrangement, circuit up ratings or the use of phase shifters, which are often quite adequate. FACTS device economics are difficult to establish – there is limited information available, mainly from prototypes, and quite understandably manufacturers are reluctant to provide information for planning purposes against the background of a limited number of applications.

LITERATURE

1. E.Acha, V.Agelidis, O.Anaya-Lara, T.Miller, 2002, "Power Electronic Control in Electrical Systems", Newnws;
2. M.T. Bina, D.C. Hamill, 2001, "A Classification Scheme for FACTS Controllers";
3. IEEE FACTS Terms & Definition Task Force, 1997, "Proposed terms and definitions for flexible AC transmission system (FACTS)," *IEEE Trans. Power Delivery*, vol. 12, no. 4, pp. 1848-1853
4. K. Habur, D. O'Leary, "FACTS – Flexible Alternating Current Transmission Systems For Cost Effective and Reliable Transmission of Electrical Energy", http://www.worldbank.org

5. R Grünbaum, M. Noroozian, B. Thorvaldsson, June 1999, “FACTS – powerful systems for flexible power transmission”, ABB Review, No.5, pp.4-17.
6. J. J. Paserba, G.F. Reed, M. Takeda, T. Aritsuka, 2001, “FACTS and Custom Power Equipment for the Enhancement of Power Transmission System Performance and Power Quality”, Symposium of Specialist in Electric Operational and Expansion Planning.
7. V. Vuckovic, 1999, “F.A.C.T.S”, XXIV Savetovanje JUKO-CIGRE, Vrnjačka Banja, Knjiga I, R14-01.
8. CIGRE JWG 14/37/38/39-24 Final Draft Report, August 2000; “FACTS technology for open access”;
9. N. Dizdarevic “Mogućnosti povećanja prijenosne moći EES-a korišćenjem konvencionalnih i FACTS naprava”, CIGRE okrugli stol “Naponske prilike u mreži 400 kV i stabilnost EES-a”, www.eihp.hr/~ndizdar.

KEY WORDS: FACT devices, SVC, TCR, STATCOM, UPFC, Custom Power, HVDC.

APPENDIX

Short terms used in the paper

DS - Dynamic Stability
FC - Fixed Capacitor, Frequency Control
NGH - Hingorani Damper
PAR - Phase-Angle-Regulator
SCCL - Super-Conducting Current Limiter
STATCOM - Static Synchronous Compensator
SVC - Static Var Compensator
TCPAR - Thyristor Controlled Phase-Angle Regulator
TCR - Thyristor Controlled Reactor
TCSC - Thyristor Controlled Series Compensator
TCT - Thyristor Controlled Transformer
TCVL - Thyristor Controlled Voltage Limiter
TSBR - Thyristor Switched Braking Resistor
TSC - Thyristor Switched Capacitor
TSSC -Thyristor Switched Series Compensator
UPFC - Unified Power Flow Controller
VC - Voltage Control