

## **Flexible AC Transmission System Controllers: A State of Art**

**Ravi Pratap Singh<sup>1</sup>, S. K. Bharadwaj<sup>2</sup>, R. K. Singh<sup>3</sup>**

*<sup>1, 2, 3</sup> Maulana Azad National Institute of Technology, Bhopal, Madhya Pradesh*

### **Abstract**

Electricity market activities and a growing demand for electricity have led to heavily stressed power systems. This requires operation of the networks closer to their stability limits. Cost effective solutions are preferred over network extensions. The flexible alternating current transmission system (FACTS), a new technology based on power electronics, offers an opportunity to enhance controllability, stability, and power transfer capability of ac transmission systems. This paper provides a comprehensive review and evaluation of FACTS controllers.

**Keywords:** Flexible AC Transmission System (FACTS), FACTS Controllers, Power Transmission, Power Flow Control.

### **Introduction**

The electricity supply industry is undergoing a profound transformation worldwide. Market forces, scarcer natural resources, and an ever-increasing demand for electricity are some of the drivers responsible for such unprecedented change. Against this background of rapid evolution, the expansion programs of many utilities are being thwarted by a variety of well-founded, environment, land-use, and regulatory pressures that prevent the licensing and building of new transmission lines and electricity generating plants.

The ability of the transmission system to transmit power becomes impaired by one or more of the following steady state and dynamic limitations:

- Angular stability,
- Voltage magnitude,
- Thermal limits,
- Transient stability, and
- Dynamic stability.

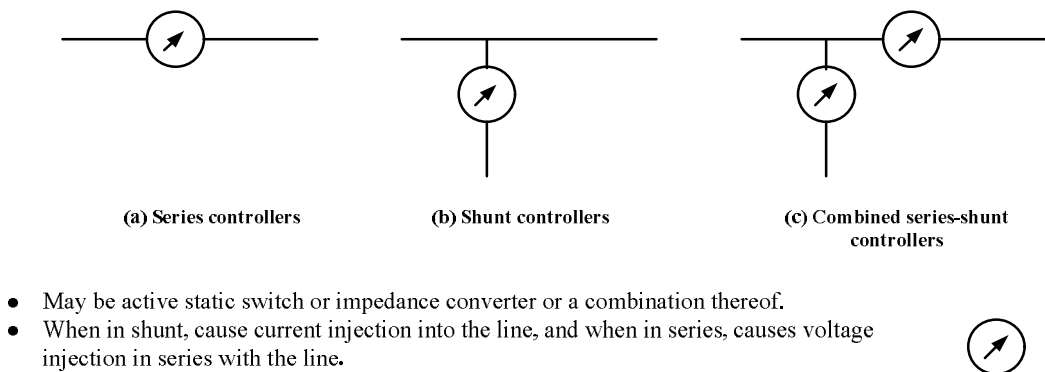
These limits define the maximum electrical power to be transmitted without causing damage to transmission lines and electrical equipment. The limitations on power transfer can always be relieved by the addition of generation and transmission lines facilities.

### FACTS Controllers

Flexible AC Transmission System (FACTS) is defined by an IEEE Working Group as: "Alternating current transmission systems incorporating power electronic-based and other static Controllers to enhance controllability and increase power transfer capability."

The significance of the power electronics and other static Controllers is that they have high-speed response and there is no limit to the number of operations. Like a transistor leads to a wide variety of processors, power devices such as Thyristor, GTO, and IGBT lead to a variety of FACTS Controllers as well as HVDC converters. These Controllers can dynamically line voltage, active and reactive power flow, and control line impedance. They can absorb or supply reactive power and with storage they can supply and absorb active power as well.

Figure 1 show, that there are three types of FACTS Controllers, all with high speed control. (a) as injection of voltage in series with the line; (b) as injection of current in shunt and the (c) a combination of voltage injection in series and current injection in shunt. These Controllers will of course have constraint according to the specific type of Controller, its characteristics and rating.



**Figure 1.** Type of FACTS Controller

### Objectives of FACTS controllers

The main objectives of FACTS controllers are the following:

- Regulation of power flows in prescribed transmission routes.
- Secure loading of transmission lines nearer to their thermal limits.
- Prevention of cascading outages by contributing to emergency control.
- Damping of oscillations that can threaten security or limit the usable line capacity.

The implementation of the above objectives requires the development of high power compensators and controllers. The technology needed for this is high power electronics with realtime operating control. The realization of such an overall system optimization control can be considered as an additional objective of FACTS controllers [1]. FACTS offers solutions to overcome constraints on useable transmission capacity. These constraints may be due to:

Dynamic conditions of :

- Transient and Dynamic Stability
- Subsynchronous Oscillations
- Dynamic Over Voltages and Under Voltages
- Voltage Collapse

Steady State conditions of :

- Undesirable Power Flow
- Excess Reactive Power Flows
- Steady State Voltage
- Thermal Limits

### **Types of FACTS controllers**

#### **(a) Static Synchronous Compensator (STATCOM)**

STATCOM is a static synchronous generator operated as a shunt-connected static var compensator whose capacitive or inductive output current can be controlled independent of the ac system voltage. The use of STATCOM as a FACTS controller is proposed in [2], [3].

#### **(b) Static Var Compensator (SVC)**

SVC is a shunt-connected static var generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters of the electrical power system (typically bus voltage). SVC is an important FACTS controller already widely in operation. Ratings range from 60 to 600 MVAR [4].

#### **(c) Thyristor Controlled Breaking Reactor (TCR)**

TCBR is a shunt-connected thyristor-switched resistor, which is controlled to aid stabilization of a power system or to minimize power acceleration of a generating unit during a disturbance [5], [6].

#### **(d) Thyristor Controlled Series Capacitor (TCSC)**

TCSC is a capacitive reactance compensator, which consists of a series capacitor bank shunted by a thyristor-controlled reactor in order to provide a smoothly variable series capacitive reactance.

#### **(e) Static Synchronous Series Compensator (SSSC)**

SSSC is a static synchronous generator operated without an external electric energy source as a series compensator whose output voltage is in quadrature with, and controllable independently of, the line current for the purpose of increasing or decreasing the overall reactive voltage drop across the line and thereby controlling the transmitted electric power [7]. The SSSC may include transiently rated energy

storage or energy absorbing devices to enhance the dynamic behavior of the power system by additional temporary real power compensation, to increase or decrease momentarily, the overall real (resistive) voltage drop across the line.

**(f) Interline Power Flow Controller (IPFC)**

IPFC is a combination of two or more SSSCs that are coupled via a common dc link to facilitate bi-directional flow of real power between the ac terminals of the SSSCs and are controlled to provide independent reactive compensation for the adjustment of real power flow in each line and maintain the desired distribution of reactive power flow among the lines [5], [8]. The IPFC structure may also include a STATCOM, coupled to the IPFC common dc link, to provide shunt reactive compensation and supply or absorb the overall real power deficit of the combined SSSCs.

**(g) Thyristor Switched Series Reactor (TSSR)**

TSSR is an inductive reactance compensator, which consists of a series reactor shunted by a thyristor-controlled reactor to provide a stepwise control of series inductive reactance [5].

**(h) Unified Power Flow Controller (UPFC)**

UPFC is a combination of STATCOM and a SSSC which are coupled via a common dc link to allow bidirectional flow of real power between the series output terminals of the SSSC and the shunt output terminals of the STATCOM and are controlled to provide concurrent real and reactive series line compensation without an external electric energy source. The UPFC, by means of angularly unconstrained series voltage injection, is able to control, concurrently or selectively, the transmission line voltage, impedance, and angle or, alternatively, the real and reactive power flow in the line. The UPFC may also provide independently controllable shunt reactive compensation. The UPFC proposed by Gyugyi [9] is the most versatile FACTS controller for the regulation of voltage and power flow in a transmission line.

**(i) Generalized Unified Power Flow Controller (GUPFC)**

GUPFC can effectively control the power system parameters such as bus voltage, and real and reactive power flows in the lines [10,11]. A simple scheme of GUPFC consists of three converters, one connected in shunt and two connected in series with two transmission lines terminating at a common bus in a substation [1]. It can control five quantities, i.e., a bus voltage and independent active and reactive power flows in the two lines. The real power is exchanged among shunt and series converters via a common dc link.

**(j) Interphase power controller (IPC)**

IPC is a series-connected controller of active and reactive power consisting, in each phase, of inductive and capacitive branches subjected to separately phase-shifted voltages. The active and reactive power can be set independently by

adjusting the phase shifts and/or the branch impedances, using mechanical or electronic switches. In the particular case where the inductive and capacitive impedance form a conjugate pair, each terminal of the IPC is a passive current source dependent on the voltage at the other terminal. The original concept of IPC was first described in [12] and the practical design aspects of a 200 MW prototype for the interconnection of the 120 kV networks were described in [13]. However, the original concept proposed in [12] has undergone modifications that are described in [14,15,16,17,18].

**Table 1: Control attributes of Various controllers**

FACTS controllers	Control attributes
STATCOM	Voltage control, VAR compensation, damping oscillations, voltage stability
SVC, TCR, TSC, TSR	Voltage control, VAR compensation, damping oscillations, transient and dynamic stability, voltage stability
TGBR	Damping oscillations, transient and dynamic stability
SSSC, TCSC, TSSC, TCSR, TSSR	Current control, damping oscillations, transient and dynamic stability, voltage stability, fault current limiting
TCPST	Active power control, damping oscillations, transient and dynamic stability, voltage stability
UPFC, GUPFC	Active and reactive power control, voltage control, VAR compensation, damping oscillations, transient and dynamic stability, voltage stability, fault current limiting
IPFC	Reactive power control, voltage control, damping oscillations, transient and dynamic stability, voltage stability

**Table 2: The role of FACTS controllers in power system operation**

Operating problem	Corrective action	FACTS controllers
Voltage limits: Low voltage at heavy load High voltage at low load High voltage following an outage Low voltage following an outage	Supply reactive power Absorb reactive power Absorb reactive power; prevent overload Supply reactive power; prevent overload	STATCOM, SVC STATCOM, SVC, TCR STATCOM, SVC, TCR STATCOM, SVC
Thermal limits: Transmission circuit overload Tripping of parallel circuits	Reduce overload Limit circuit loading	TCSC, SSSC, UPFC, IPC TCSC, SSSC, UPFC, IPC
Loop flows: Parallel line load sharing Post-fault power flow sharing Power flow direction reversal	Adjust series reactance Rearrange network or use thermal limit actions Adjust phase angle	IPC, SSSC, UPFC, TCSC IPC, SSSC, UPFC, TCSC IPC, SSSC, UPFC

Because the voltage, current, impedance, real power, and reactive power are interrelated, each controller has multiple attributes of what they can do in terms of controlling the voltage, power flow, stability and so on. Table 1 presents a checklist of control attributes for various FACTS controllers [4]. Table 2 presents the role of FACTS controllers in power system operation [19]. Table 3 shows Installed costs comparison of HVDC and FACTS.

**Table 3: Cost Comparison of HVDC and FACTS**

<b>Throughput MW</b>	<b>HVDC 2 Terminal</b>	<b>FACTS</b>
200 MW	\$ 40-50 M	\$ 5-10 M
500 MW	\$ 75-100 M	\$ 20-20 M
1000 MW	\$ 120-170 M	\$ 20-30 M
2000 MW	\$ 200-300 M	\$ 30-50 M

### **Benefits of FACTS controllers**

FACTS controllers enable the transmission owners to obtain, on a case-by-case basis, one or more of the following benefits:

1. Cost: Due to high capital cost of transmission plant, cost considerations frequently overweigh all other considerations. Compared to alternative methods of solving transmission loading problems, FACTS technology is often the most economic alternative [20].
2. Environmental impact: In order to provide new transmission routes to supply an ever increasing worldwide demand for electrical power, it is necessary to acquire the right to convey electrical energy over a given route.
3. Control of power flow to follow a contract, meet the utilities own needs, ensure optimum power flow, minimize the emergency conditions, or a combination thereof.
4. Contribute to optimal system operation by reducing power losses and improving voltage profile.
5. Increase the loading capability of the lines to their thermal capabilities, including short term and seasonal.
6. Increase the system security by raising the transient stability limit, limiting short-circuit currents and overloads, managing cascading blackouts and damping electromechanical oscillations of power systems and machines.
7. Provide secure tie line connections to neighboring utilities and regions thereby decreasing overall generation reserve requirements on both sides.
8. Provide greater flexibility in sitting new generation.
9. Reduce reactive power flows, thus allowing the lines to carry more active power.
10. Reduce loop flows.
11. Increase utilization of least cost generation.
12. Overcome the problem of voltage fluctuations and in particular, voltage fluctuations.

**Conclusions**

This paper has presented various FACTS controllers and analyzed their control attributes and benefits. FACTS controllers can be utilized to increase the transmission capacity, improve the stability and dynamic behaviour or ensure better quality in modern power systems. Their main capabilities are reactive power compensation, voltage control and power flow control. Due to their controllable power electronics, FACTS controllers always provide fast control actions in comparison to conventional devices like switched compensation or phase shifting transformers with mechanical on-load tap changers.

In deregulated electricity markets, the operation of the transmission network will be closer to its physical limits. The necessity to design electric power networks providing the maximal transmission capacity and at the same time resulting in minimal costs is a great engineering challenge for which a powerful solution is FACTS controllers.

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