Advanced Power Electronics Based FACTS Controllers: An Overview

S. K. Srivastava[1]

Abstract – With the ever-increasing complexities in power systems across the worldwide, especially opening of electric power markets, it becomes more and more important to provide stable, secure, controlled and high quality electric power on today's environment. The deregulation and competitive environment in the contemporary power networks will imply a new scenario in terms of load and power flow condition and so causing problems of line transmission capacity. Hence, there is an interest in better utilization of available power system capacities by installing new devices such as Flexible AC Transmission systems. The idea behind the FACTS concept is to enable the transmission system to be an active element in increasing the flexibility of power transfer requirements and in securing stability of integrated power system. In this paper some developed FACTS devices and their control features have been critically reviewed, also highlights some underdeveloped FACTS devices and their controllers, which are under testing and R & D stage.

Keywords – Flexible AC transmission systems, FACTS controllers, deregulated power system, electricity market.

I. INTRODUCTION

Since last decade, with the deregulation of the electricity market, the traditional concepts and practices of power systems have changed. These changes have been prompted due to following reasons: lack of adequate funds to set up the required generation, transmission and distribution facilities, and to bring in improvement in overall efficiency of system. The deregulated structure is aimed at abolishing the monopoly in the generation and trading sectors, thereby, introducing competition at various levels wherever it is possible.

For better utilization of the existing power system, to increase power transfer capability, installing FACTS (Flexible AC Transmission Systems) devices becomes imperative [1,5,6]. FACTS devices can control the parameter and variables of the transmission line, i.e. line impedance, terminal voltages, and voltage angles in a fast and effective way. The benefit brought about by FACTS includes improvement of system dynamic behavior and thus enhancement of system reliability and loadability. However, their main function is to control power flows [6-9], provided that they are placed at optimal locations. These aspects are playing an increasingly significant role in the operation and control of the deregulated electricity market.

The flexible AC transmission system is akin to high voltage DC and related thyristor developments, designed to overcome the limitations of the present mechanically controlled AC power transmission systems. By using reliable and high-speed power electronic controllers, the technology offers five opportunities for increased efficiency of utilities.

- Greater control of power so that it flows on the prescribed transmission routes.
- Secure loading of transmission lines to levels nearer their thermal limits.
- Greater ability to transfer between controlled areas.
- Prevention of cascading outages.
- Damping of power system oscillation.

The increased interest in these devices is essentially due to two reasons. Firstly, the recent development in high power electronics has made these devices cost effective and secondly, increased loading of power systems, combined with deregulation of power industry, motivates the use of power flow control as a very cost-effective means of dispatching specified power transactions. Several emerging issues in competitive power market, namely, as congestion management, enhancement of security and available transfer capability of the system, transmission pricing, etc. have been restricting the free and fair trade of electricity in the open power market. FACTS devices can play a major role in these issues. Moreover, it is important to ascertain the location for placement of these devices because of their considerable costs. The insertion of such devices in electrical systems seems to be a promising strategy to reduce the power flows in heavily loaded lines resulting in increased system loadability, low system loss, improved stability of the network and reduced cost of production. Also, reduces mitigation of power quality problems such as voltage sag, swell & interruption [29].

Newer generations of FACTS controllers such as HVDC Light from ABB are based on high frequency Pulse Width Modulation (PWM) voltage source converters. To meet the demands for higher power PWM voltage source converters, renewed efforts have been made to improve the GTO. The integrated gate commutating thyristor (IGCT) developed by ABB is an example of this effort. In the IGCT a specially developed GTO that has very low gate stray inductance is connected to a negative power supply through low on-resistance MOSFET. This arrangement allows IGCT be turned off without a snubber and can be used at higher frequencies [27]. Another latest device, emitter turn-off thyristor (ETO) have disused by authors [26], to reduce cost further and to reduce the auxiliary power consumed by the IGCT. The ETO is based on the mature technology of the GTO and power MOSFET; the ETO provides a low cost solution for megawatts PWM VSC applications.

The FACTS devices can be categories as shunt, series, series-series and combine shunt-series controllers [5,7] namely, static VAR compensator (SVC), thyristor controlled series capacitor (TCSC), thyristor controlled phase angle regulator (TCPAR), static compensator (STATCOM), static synchronous series compensator (SSSC), unified power flow controller (UPFC), generalized unified power flow controller (GUPFC) and interline power flow controller (IPFC) etc.

By use of such controllable devices, line power flows can be changed in such a way that thermal limits are not violated, losses minimized, stability margin increased and contractual requirement fulfilled without violating specified power dispatch.

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[1] Department of Electrical Engineering, M. M. M Engineering College Gorakhpur, India. E-mail: sudhirksr@yahoo.co.in

Static Var compensator (SVC) improves the system performances by controlling the magnitude of voltage. Thyristor controlled phase angle regulator (TCPAR) controls the phase angle of voltage, while thyristor controlled series compensator (TCSC) changes the effective impedance of transmission line to the system performance. The unified power flow controller (UPFC) offers to combine all three functions in one device [2,3]. The control of system parameters can be carried out concurrently or sequentially with transfer from one type control (phase shift) to another one (series compensation) in real time. The other devices of FACTS controller family are static compensator (STATCOM), static synchronous series compensator (SSSC), generalized unified power flow controller (GUPFC) and interline power flow controller (IPFC) etc. [23, 25,28].

This paper has focused some developed FACTS controllers and their control features under deregulated environment of power market. A simple UPFC and generalized UPFC (GUPFC) controller has been suggested to enhance its capabilities such as to increase the transmission capability by capacitive reactance compensation, or to span large voltage phase angles between the sending and receiving ends while operating as a phase shifter or to reverse the direction of power flow. This paper also highlights some advanced FACTS controllers at R & D stage.

II. OVERVIEW OF DEVELOPED FACTS DEVICES

The SVC for voltage control was first demonstrated in Nebraska and commercialized by GE in 1974 and by Westinghouse in Minnesota in 1975. Static Var Compensator, composed of thyristor switched capacitor (TSC) and thyristor controlled reactor (TCR) shown in Fig. 1. With proper co-ordination of the capacitor switching and reactor control, the VAR output can be varied continuously between the capacitive and inductive ratings of the equipment [1,5].

In TCSC the degree of series increasing or decreasing the number of capacitor banks in series controls compensation. The TCSC can be effective in transient stability improvement; power oscillation damping and balancing power flow in parallel lines. The basic TCSC scheme is shown in Fig. 1.1

Working principle of TCPAR is identical with a phase shifting transformer with a thyristor type tap changer and could be applied to regulate transmission angle to maintain balance power flow in multiple transmission paths, or to control it so as to increase the transient and dynamic stabilities of the system [23,24]. The basic scheme of TCPAR is shown in Fig. 1.2.

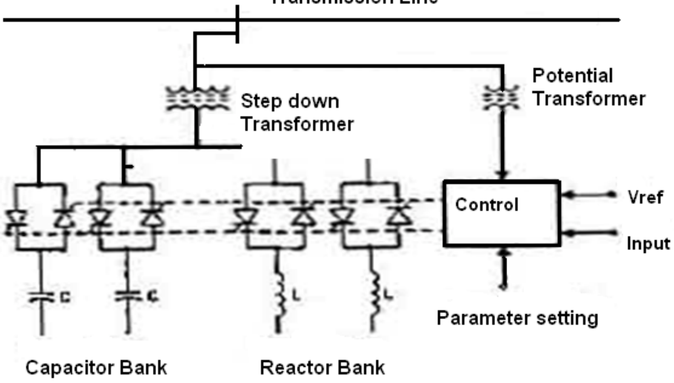

Fig. 1: SVC using TSC and TCR

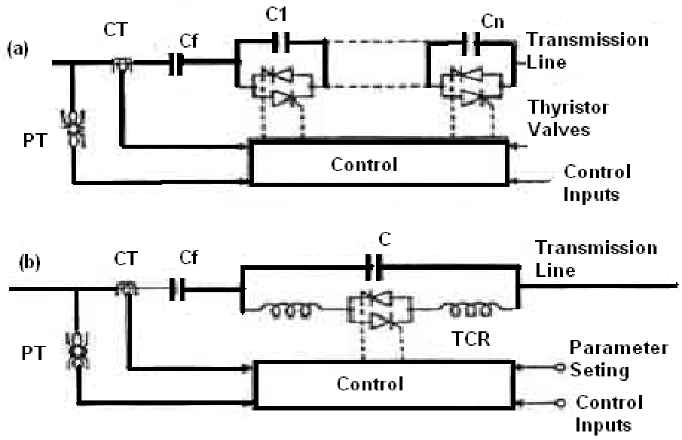

Fig. 1.1: TCSC using (a) TSC (b) TCR

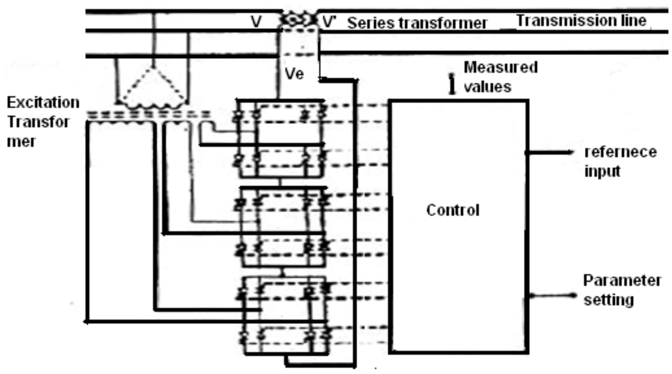

Fig. 1.2: Thyristor controlled Phase angle regulator

III. CONVERTER BASED FACTS CONTROLLERS

A. STATic CONdensor (STATCON)

The working of STATCON is based on the use of Gate Turn Off thyristors (GTO) [7] in building a voltage source inverter driven from a voltage source across DC storage capacitors. EPRI and Tennessee Valley Authority (TVA) had developed and installed ±100 MVAR STATCON at the Sullivan substation on TVA power system in New York.

B. Static Synchronous Compensator (STATCOM)

The STATCOM [7-9] is a state-of-the-art Flexible AC Transmission System (FACTS) technology that uses advanced power semiconductor switching techniques to provide dynamic voltage support, power system stabilization, and enhanced power quality for transmission and distribution system applications.

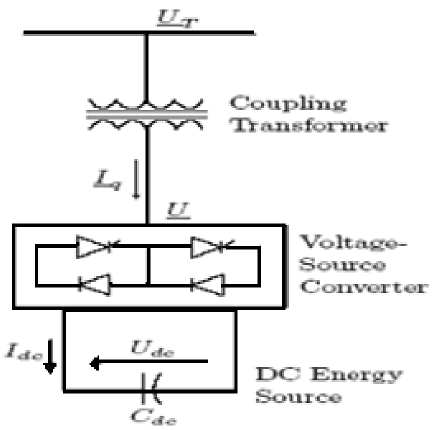

Fig. 2: Static Compensator (STATCOM)

Basically it is a controlled reactive-power source, which provides voltage support by generating or absorbing reactive power at the point of common coupling without the need of large external reactors or capacitor banks. The basic voltage-source converter scheme is shown in Fig. 2.

As shown in Fig. 2, the charged capacitor C_{dc} provides a dc voltage to the converter, which produces a set of controllable three-phase output voltages with the frequency of the ac power system. By varying the amplitude of the output voltage, the reactive power exchange between the converter and the ac system can be controlled.

The d-q frame model and steady state characteristics of the CSI based STATCOM has reported [21], which results rapid non oscillatory dynamics of ac current without overshoot or steady state error.

C. Static Synchronous Series Compensator (SSSC)

The SSSC [4,5,7] can be considered as a impedance compensation controller acting like a controlled series capacitor. It consists a solid-state voltage source inverter, injecting an almost sinusoidal voltage, of variable magnitude, in series with a transmission line. It compensates the inductive voltage drop in the line by inserting capacitive voltage in order to reduce the effective inductive reactance of the transmission line. In contrast to series capacitor, the SSSC is able to maintain a constant compensating voltage in case of variable line current or controls the amplitude of the injected compensating voltage independent of amplitude of line current. A simply connected SSSC with transmission line is shown in Fig. 3.

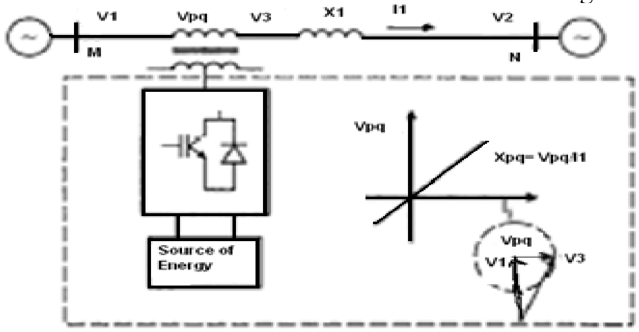

Fig. 3: Static Synchronous Series Compensator

The SSSC has wider control range than the controlled series capacitor of same MVA rating for practical application point of view in steady state power flow control or stability improvement. Also in [16], the on-line fuzzy control of SSSC has been reported in order to improve the transient stability limit, damping out the system oscillation, control the voltage regulation and overall enhancement of power transfer capacity.

D. Interline Power Flow Controller (IPFC)

The IPFC [9] is a generalized and multi-functional FACTS controller. The IPFC addresses the problem of compensating a number of transmission lines at a given substation. Series capacitive compensators are used to increase the transmittable active power over a given line but they are unable to control the reactive power flow in, and thus the proper load balancing of the line. With IPFC active power can be transferred between different lines. Therefore, it is possible to:

- Equalize both active and reactive power flow between the lines,
- Reduce the burden of overloaded lines by active power transfer,
- Compensate against resistive line voltage drops and the corresponding reactive power demand,
- Increase the effectiveness of the overall compensating system for dynamic disturbances.

The capability of the IPFC is facilitated by a number of voltage-sourced converters (VSCs) as shown in Fig. 4, which are connected back-to-back at their dc terminals. Each VSC is coupled to a different transmission line via series coupling transformer and is able to provide independent series reactive compensation, as an SSSC, to its own line. However, the converters can transfer active power among them via their common dc terminal [9,10]. A multi-converter IPFC configuration allows the IPFC to provide reactive power series compensation in one series branch, and to provide both active and reactive compensation for the remaining series branch.

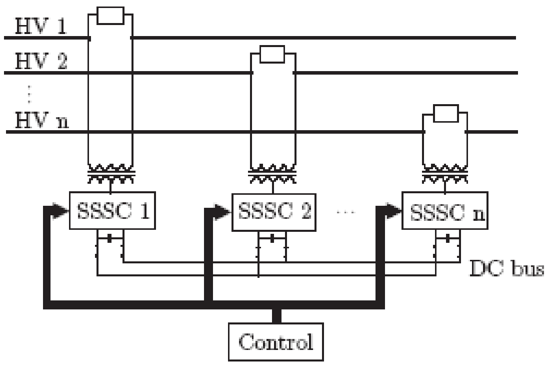

Fig. 4: Interline Power Flow Controller (IPFC)

E. Unified Power Flow Controller (UPFC)

The basic components of the UPFC are two voltage source inverters (VSI's) sharing a common dc storage capacitor, and connected to the system through coupling transformers. One VSI is connected in shunt to the transmission system via a shunt transformer, while the other one is connected in series through a series transformer. A basic UPFC functional scheme is shown in Fig. 5.

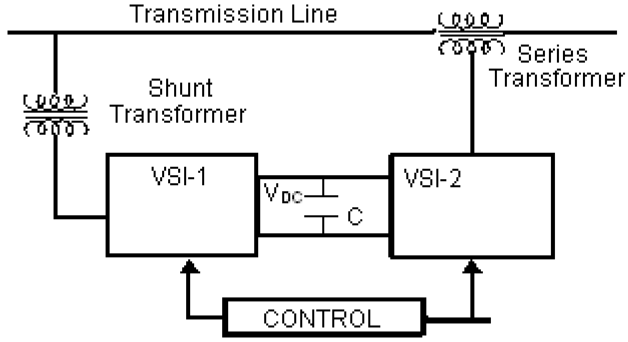

Fig. 5: Basic structure of UPFC

The UPFC has many possible operating modes [2,15]. In particular, the shunt inverter is operating in such a way to inject a controllable current i_{sh} into the transmission line. This current consists of two components with respect to the line voltage: the real or direct component i_{shd}, which is in phase or in opposite phase with the line voltage, and the reactive or quadrature component, i_{shq}, which is in quadrature. The direct component is automatically determined by the requirement to balance the real power of the series inverter. The quadrature component, instead, can be independently set to any desired reference level (inductive or capacitive) within the capability of the inverter, to absorb or generate respectively reactive power from the line. So, two control modes are possible:

A. VAR Control Mode:

In this, the reference input is an inductive or capacitive var as request. The shunt converter control translates the var reference in to a corresponding shunt current request and adjusting the gating of the converter to established the desired current.

B. Automatic Voltage Control Mode:

In this the goal is to maintain the transmission line voltage at the connection point to a reference value. Instead, the series inverter injecting the voltage V_{se} controllable in amplitude and phase angle in series with the transmission line influences the power flow on the transmission line. The injected series voltage can be determined in different ways:

C. Direct Voltage Injection Mode:

The reference inputs are directly the magnitude and phase angle of the series injected voltage. When the injected voltage is kept in phase with the system voltage or in quadrature with the line current, provides series reactive compensation.

D. Phase Angle Shifter Emulation Mode:

The reference input signal is phase displacement between the two ends of bus voltages. The injected voltage is controlled with respect to input bus voltage so that the output bus voltage is phase shifted by an angle specified by the reference input.

E. Line Impedance Emulation Mode:

In line impedance mode, the magnitude of the injected voltage vector V_{pq} is controlled in proportion to the magnitude of line current, so it emulates reactive impedance. The reference input is an impedance value to insert in series with the line impedance.

F. Automatic Power Flow Control Mode:

In automatic power flow control mode, the series injected voltage is determined automatically and continuously by a closed loop control system to ensure that the desired *P* and *Q* are maintained despite system changes. The reference inputs are values of P and Q to maintain on the transmission line despite system changes.

For simplification of control analysis and to improve the dynamic performance of UPFC, various control strategies including d-q axis control have been reported by authors. Some have described the dynamic modeling of UPFC with conventional PI & PID based control techniques [4,5]. Whereas in papers [12-14], fuzzy-rules based controllers of UPFC have been suggested to regulate the power system parameters and improving the dynamic performances. In fuzzy logic, the controller is represented as a set of rules. These rules are obtained from human experts based knowledge and observations. Fuzzy rules based logic controller has a number of distinguished advantages over the conventional PI [16-20], as it is not so sensitive to the variation of system structure, parameters, and operation points. The control law developed by fuzzy can be easily implemented in a large-scale nonlinear system.

It has been suggested [17], neural network based control approach of UPFC by single neuron and multi-neuron radial basic function controller (RBFNN). The single neuron controller uses either the real and reactive power deviations or real power and voltage deviations at the UPFC junction bus to provide better damping performance and transient stability limit as that of existing PI controllers.

IV. UNDER DEVELOPED FACTS DEVICES

(i) Generalized Unified Power Flow Controller (GUPFC)

The Generalized Unified Power Flow Controller (GUPFC) is one of the latest generation FACTS device that can control bus voltage and power flows of more than one line or even sub-network [6,10,22]. The simple GUPFC consisting of three converters, as shown in fig. 6.0, one shunt connected and two in series with transmission lines, is capable of simultaneously controlling five power system quantities, i.e. the bus voltage at substation, real and reactive power flows on two lines of existing the substation.

The GUPFC has the similar structure with the IPFC except that *VSC1* is shunt-connected at bus-1, shown in fig. 6.0. The *VSC1* is responsible for balancing the active power required by the series converters and also provides shunt reactive compensations to regulate the voltage magnitude at bus-1. The series converters, *VSC2 – VSCn*, can provide active and reactive power compensation simultaneously to control the active and reactive power of their series connected transmission.

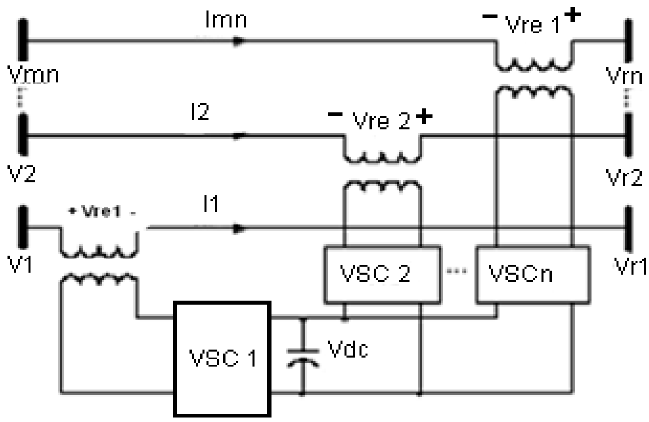

Fig. 6: Basic structure of Generalized unified power flow controller (GUPFC)

For control of GUPFC, proportional-integral (PI) loops are utilized. In this scheme the gains of controller parameters are being selected to provide stable operation of GUPFC under steady state and faulty conditions.

The GUPFC, as proposed in [10], can also be used in modeling other members of the CSC family in power flow and OPF analysis. The strong control capability of the GUPFC with controlling bus voltage and multi-line power flows offers a great potential in solving many of problems facing the electric utilities in a competitive environment.

(ii) Convertible Static Compensator (CSC)

The Convertible Static Compensator (CSC) is the latest generation of FACTS controller family [13], providing the flexibility for adaptation to power system control needs and enable unique control capabilities of power systems. The CSC is being installed at NYPA's Marcy 345-KV substation near Utica, New York. It is a combination of FACTS and conventional technologies. On fully implementation, this will provide a long term solution for the power transfer, improving voltage, power flow control, enhance the reliability and resiliency of the network.

A. CSC Configuration and Operational Modes

The CSC will be able to utilize two inverters in different configurations such as STATCOM, SSSC, UPFC and IPFC. The conceptual structure of CSC is shown in Fig. 7. The CSC can be deployed on the transmission system in 11 configurations. The control mode determines the functionality of CSC in a particular configuration. Sequence and interlock control logic is to be implemented for automatic changes from one configuration to another.

B. CSC Operation and Control

The CSC control structure consists of inner and outer loops. The inner loop controller is designed to provide the magnitude and angle controlled synchronous voltage source, which is utilized for voltage and power regulation. The outer loop is required for damping of power system oscillations. The purpose of damping controller is to increase the resiliency of high voltage transmission system by adding positive damping during severe system contingencies. The control structure of CSC is shown in Fig. 8.

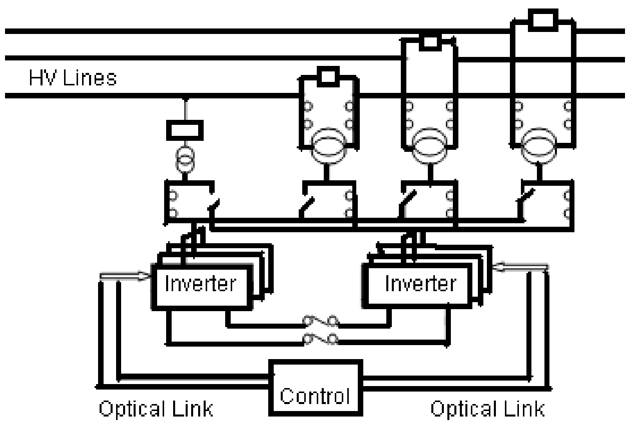

Fig. 7: CSC conceptual structure

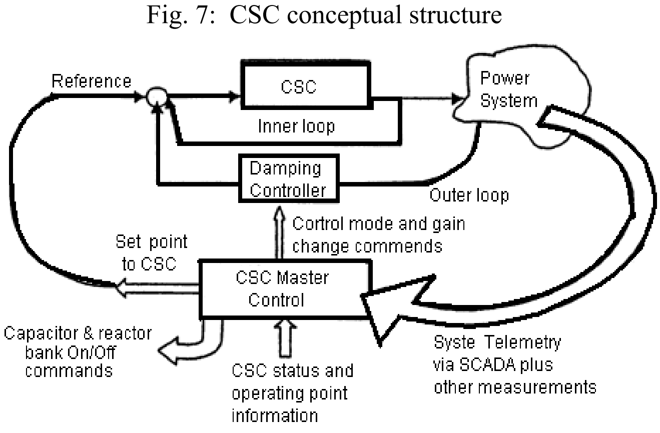

Fig. 8: CSC control structure

V. CONCLUSION

This paper presents a review of developed and under-developing power electronics-based FACTS devices and their control features. Various FACTS controller can enhance the power system performance, both static and dynamic, considerably. Series FACTS controllers such as SSSC, IPFC, UPFC, GUPFC and more recently CSC are being utilized in different applications. The acceptability of new concept of multi-line power compensation in the GUPFC or multi-line UPFC, which can control bus voltage and power flows of more than one line or sub-network, is growing rapidly. The CSCs are still to be practically examined for relieving in transmission line congestion, damping out system oscillations at lower frequencies

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BIOGRAPHY

S.K Srivastava obtained his B.Tech , M.Tech and Ph.D Degrees from M.M.M Engineering College Gorakhpur (India) ,I.I.T Delhi (India) & UP Technical University Lucknow (India) in the year 1986, 1993 & 2008 respectively. He is a faculty member in the Department of Electrical Engineering of M.M.M Engineering College Gorakhpur (U.P), India. His research interest includes power system operation and control, FACTS, deregulations, Fuzzy & Neural applications in power system problems.