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A Review on FACTS Technology

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***Abstract*—One aspect of the power electronics revolution that is taking place in all areas of electric energy is Flexible AC Transmission systems (FACTS). This paper deals with the introduction and review on application of various FACTS controllers such as SVC, STATCOM, SSSC, TCSC, UPFC for improvement of performance parameters of power systems such as to improve the voltage profile, to minimize the active power losses, enhancement of damping ratio of power systems, to provide various flexible operations of power systems, increased the loadability, improve the transient and steady-state stability, increased the available transfer capacity, etc. Author strongly believe that this write-up will be very useful for the practitioners, researchers and scientific engineers for finding out the relevant reference in the field of the various FACTS controllers for control, planning, operation and protection of power systems.**

Keywords—FACTS, Power systems, SVC, SSSC, STATCOM, TCSC, UPFC.

I. INTRODUCTION

Growing Electricity demand and market activities for electricity have governed to heavily stressed power systems. Now-a-days, worldwide the electricity supply industry is going through profound transformation. These changes are continuously being proposed to a once predictable business with the increasing electricity utility industry and the ongoing expansion. Due to these increasing demand of electrical energy consumption forces the electrical power utilities to provide a high quality of electrical power and these is the reason why these issue is getting more and more importance in power systems. In order to enhance the quality of electrical power a new technology based on power electronics named as Flexible AC Transmission systems (FACTS) is being introduced in the year 1988 by Dr. N. Hingorani. These FACTS concept is based on the consequential incorporation of power electronics devices and methods into the high-voltage side of the network to make it electronically controllable. Due to rapid development of the modern power electronics technology up-till now lots of advanced FACTS devices have been put forward.

These FACTS technology offers a favorable condition to improve controllability, power transfer capability and stability of AC transmission systems, and also overcome the operational complexities with conventional method of power compensation.

II. CONCEPT OF FACTS TECHNOLOGY

According to IEEE, FACTS and FACTS controller is defined as follows :

A. FACTS (Flexible AC Transmission systems)

Alternating current transmission systems incorporating power electronics based and other static controllers to enhance controllability and increase power transfer capability.

B. FACTS Controller

Power Electronics based system and other static equipment that provides control of one or more AC transmission system parameters.

According to Siemens (German multinational engineering and electronics conglomerate company) FACTS is "The technology which Increase the reliability of AC grids and reduce power delivery costs. They improve transmission quality and efficiency of power transmission by supplying inductive or reactive power to the grid."

FACTS technology is not a single high-power controller, but rather a collection of controllers which can be applied individually or in co-ordination with others to control one or more of the inter-related system parameters.

In general, the FACTS controllers can be classified as follows:

- Thyristor controlled based FACTS controllers
- VSI based FACTS controllers

But out of the above two controllers VSI based controllers are much more better then Thyristor controlled based controllers as these controllers posses a drawback of resonance phenomena whereas VSI based FACTS controllers are free from this phenomena.

III. GENERATION OF FACTS CONTROLLERS

The following generation of FACTS controllers for development of FACTS Controllers.

- First Generation of FACTS Controllers

FACTS controllers such as SVC, TCSC, TCPST are developed in the first generation of FACTS controllers.

- Second Generation of FACTS Controllers

FACTS controllers such as SSSC, STATCOM, UPFC are developed in the second generation of FACTS technology.

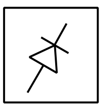
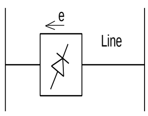
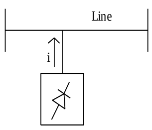
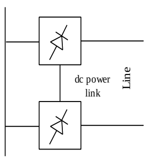
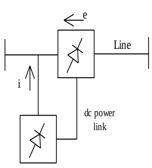
IV. BASIC TYPES OF FACTS CONTROLLERS AND THEIR FUNCTIONS

In general, FACTS controllers can be divided into four categories on the basis of their connection diagrams in power systems mentioned in TABLE 1:

A. Series Connected FACTS devices:

Series FACTS devices could be variable impedance such as reactor, capacitor, etc., or power electronics based variable source of main frequency, sub synchronous and harmonics frequencies (or a combination) to serve the desired need. In principle, all series FACTS devices inject voltage in series with the transmission line.

TABLE 1. BASIC TYPES OF FACTS CONTROLLERS

No.	Symbol	Description
1		- General symbol for FACTS controller.
2		- Known as series FACTS controller such as TCSC. - The controllers inject voltage in quadrature with the line current. - The controllers supply / absorb variable RP.
3		- Known as shunt FACTS controller such as SVC, STATCOM. - The controllers inject capacitive or inductive current in quadrature with the line voltage. - The controllers supply / absorb variable RP.
4		- Known as combined series-series FACTS controller such as IPFC. - It is a combination of separate series controllers. - Provide independent series RP compensation for each line. - Transfer AP among the lines via the dc power link.
5		- Known as combined series-shunt controller such as UPFC etc. - It is a combination of separate series and shunt controller. - Provide series and shunt AP compensation. - Transfer AP between the series and shunt controllers via the dc power link.

B. Shunt Connected FACTS devices:

Shunt FACTS devices may be variable impedance, variable source, or a combination of these. They inject current into the system at the point of connection.

C. Combined Series-series Connected FACTS devices:

Combined series-series FACTS devices is a combination of separate series FACTS devices, which are controlled in a coordinated manner.

D. Combined Series-shunt Connected FACTS devices:

Combined series-shunt FACTS devices is a combination of separate shunt and series devices, which are controlled in a coordinated manner or one device with shunt and series elements.

V. CONTROL ATTRIBUTES FOR VARIOUS FACTS CONTROLLERS

Following Table 2 deals with control attributes for various FACTS Controllers:

TABLE 2. CONTROL ATTRIBUTES FOR VARIOUS FACTS CONTROLLERS

No.	FACTS Controller	Control Attributes for various FACTS Controllers
1	SVC	Voltage control, VAR compensation, Power Oscillation Damping, Voltage Stability, Transient Stability and Distributed Generations
2	TCSC	Current control, Power Oscillation Damping, Voltage Stability, Transient Stability and Distributed Generations, Fault Current Limiting.
3	SSSC without storage	Current control, Power Oscillation Damping, Voltage Stability, Transient Stability and Distributed Generations, Fault Current Limiting.
4	SSSC with storage	Current control, Power Oscillation Damping, Voltage Stability, Transient Stability and Distributed Generations.
5	STATCOM without storage	Voltage control, VAR compensation, Power Oscillation Damping, Voltage Stability.
6	STATCOM with storage, BESS, SMES, large dc capacitor	Voltage control, VAR compensation, Power Oscillation Damping, Voltage Stability, Transient Stability and Distributed Generations, AGC.
7	UPFC	Active Power and Reactive Power control, voltage control, VAR compensation, Power Oscillation Damping, Voltage Stability, Transient Stability and Distributed Generations, Fault Current Limiting.

VI. INTRODUCTION TO VARIOUS FACTS CONTROLLERS

A. SVC (Static VAR Compensator):

According to IEEE-CIGRE co-definition, a SVC (Static VAR Compensator) is a static VAR generator whose output is varied so as to control or maintain specific parameters (e.g. voltage or reactive power of bus) of the electric power system.

SVC are used in two main situations:

- Connected near large industrial loads, to improve power quality i.e. Industrial SVC.
- Connected to the power system, to regulate Transmission voltage i.e. Transmission SVC.

The SVC can be operated in two different modes:

- In voltage regulation mode (the voltage is regulated within a certain specified limits.)
- In VAR control mode (the SVC susceptance is kept constant.)

Basic circuit for a Static VAR Compensator (SVC) is shown in figure 1 and its voltage-current characteristics is shown I figure 2. In figure 2, the voltage V_{ref} is the terminal voltage of the SVC when it is neither generating nor absorbing any reactive power. The reference voltage value can be varied between the maximum and minimum limits, V_{ref} max and V_{ref} min, using SVC control system. The V-I characteristics is described by the following equations:

$V = V_{ref} + X_s * I$ if SVC is in regulation range $(-Bc_{max} < B < Bl_{max})$ (1)

$V = -\frac{I}{Bc_{max}}$ if SVC is fully capacitive $(B = Bc_{max})$ (2)

$V = -\frac{I}{Bl_{max}}$ if SVC is fully inductive $(B = Bl_{max})$ (3)

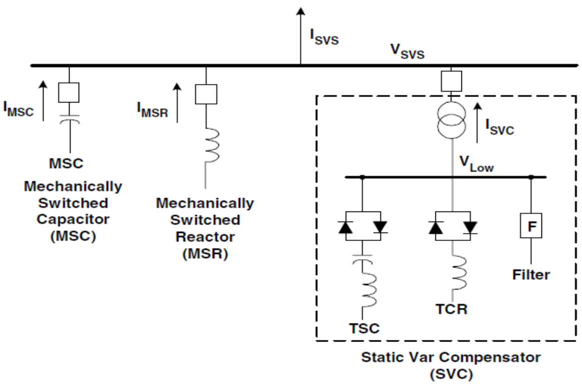


Fig. 1 Circuit for Static VAR compensator

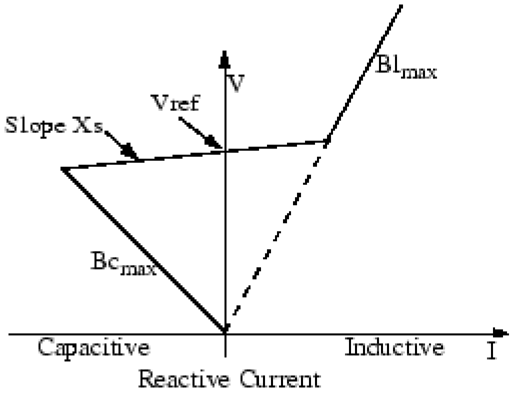


Fig. 2 Voltage – Current Characteristics

B. TCSC (Thyristor Controlled Series Capacitor)

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

TCSC designs operates in a same way as Fixed Series Compensation but it provide variable control of the reactance absorbed by the capacitor bank. The basic circuit diagram of TCSC is shown in figure 3.The effective reactance is the parallel combination of a variable reactance and fixed capacitor. At certain values of firing angle parallel resonance may occur. The X-I characteristics of TCSC is shown in figure 4.

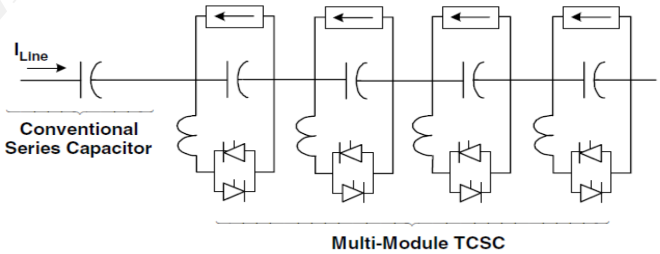


Fig. 3 Basic circuit diagram of TCSC.

TCSC has three basic modes of operation:

- Thyristor valve blocked mode:

  $\alpha_{L\,lim} \le \alpha \le \alpha_{C\,lim}$

  Resonance region for in inhibited operation

- Thyristor valve bypass mode:

  $0 \le \alpha \le \alpha_{L\,lim}$

  Inductive region operation

- Capacitive boost mode (Vernier control mode):

  $\alpha_{C\,lim} \le \alpha \le \frac{\pi}{2}$

  Capacitive region operation

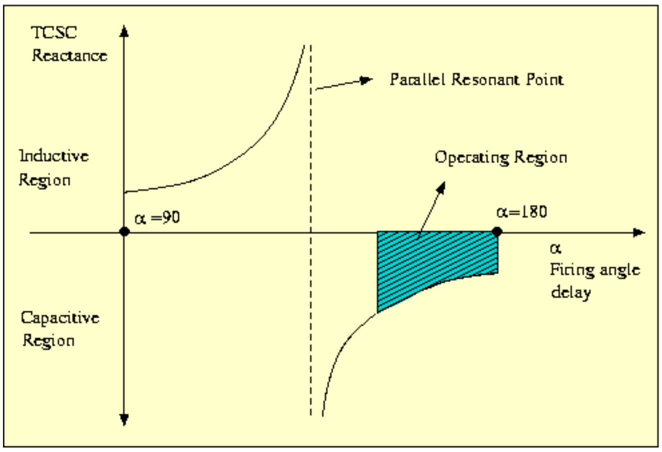


Fig. 4 X-I characteristics of TCSC

C. SSSC (Static Synchronous Series Compensator)

A 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. The SSSC may include transiently rated energy source or energy absorbing device to enhance the dynamic behavior of the power system by additional temporary real power compensation, to increase or decrease momentarily, the overall real voltage drop across the line.

The SSSC is a device that belongs to the FACTS family using power electronics to improve power oscillation damping and to control power flow on power grids. The SSSC injects a voltage in series with the transmission line where it is connected. The SSSC contains a solid-state voltage source inverter connected in series with the transmission line through an insertion transformer. This connection enables the SSSC to control power flow in the line for a wide range of system conditions. Figure 5 shows the basic circuit diagram of SSSC and figure 6 shows Elementary Two-machine system with SSSC and associated Phasor diagram.

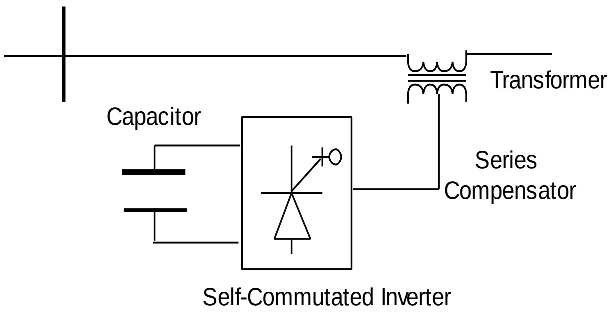


Fig. 5 Basic circuit of SSSC

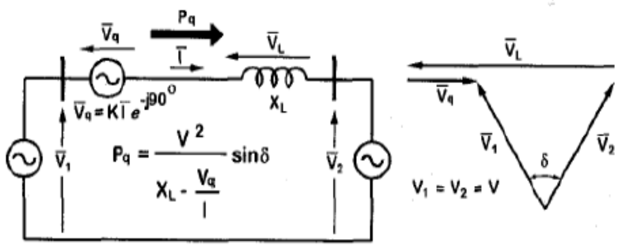


Fig. 6 Elementary Two-machine system with SSSC and associated Phasor diagram.

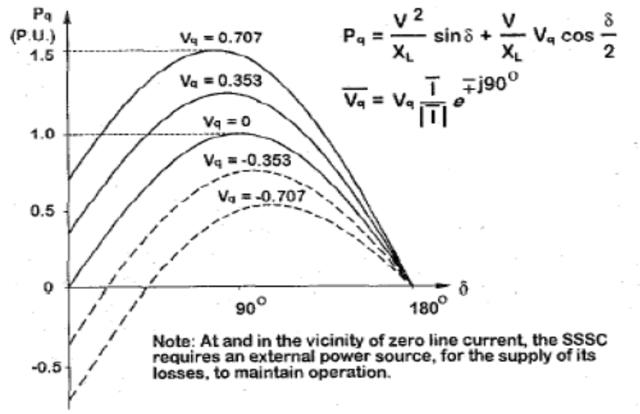


Fig. 7 Transmitted power P_q Vs transmission angle δ as a parametric function of the series compensating voltage V_q provided by SSSC.

SSSC injects the compensating voltage in series with the line irrespective of line current. Figure 7 shows the transmitted power P_q Vs transmission angle δ as a parametric function of the series compensating voltage V_q and it can be expressed for two – machine system as follows:

$$P_q = \frac{V^2 \sin\delta}{X_L} + \frac{V}{X_L} V_q \cos\frac{\delta}{2}$$

D. STATCOM (Static Synchronous Compensator)

A 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.

Figure 8 shows the basic circuit of STATCOM and when the STATCOM is operated in voltage regulation mode, it implements the V-I characteristics as shown in figure 9 below.

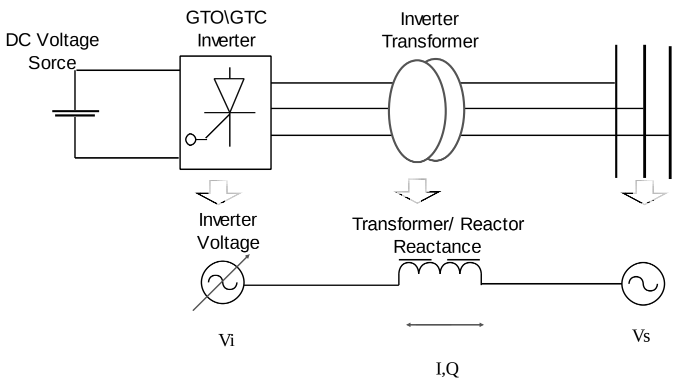


Fig. 8 Basic circuit of STATCOM

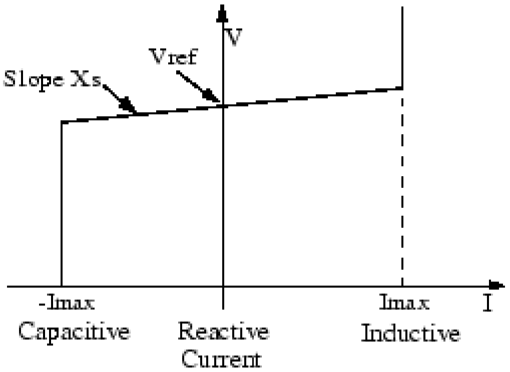


Fig. 9 V-I characteristics of STATCOM

STATCOM can be operated in following different modes as shown in TABLE 3 below :

TABLE 3. OPERATION MODES OF STATCOM

Mode	Phasor	Description
No load mode (Normal excited mode of operation)	Vs Vc	If $V_c = V_s$, $I_{cs} = 0$
Capacitive Operation mode (Over excited mode of operation)	jX*Ics Ics Vs Vc	If $V_c > V_s$, I_{cs} appears to be leading current. Since the magnitude of the current can be controlled continuously by adjusting V_c the STATCOM will function as a capacitor whose capacitive reactance is continuously controllable.
Inductive Operation mode (Under excited mode of operation)	Vs Vc jX*Ics	If $V_s < V_c$, I_{cs} appears to be lagging current. In this mode, the STATCOM will function as a reactor whose inductive reactance is continuously controllable.

In STATCOM , the resonance phenomenon has been removed. So, STATCOM is having more superior performance as compared to a SVC.

E. UPFC (Unified Power Flow Controller)

A combination of Static synchronous compensator (STATCOM) and a static synchronous series compensator (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 angularity 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.

Figure 10 shows single line diagram of a UPFC and phasor diagram of voltage and current.

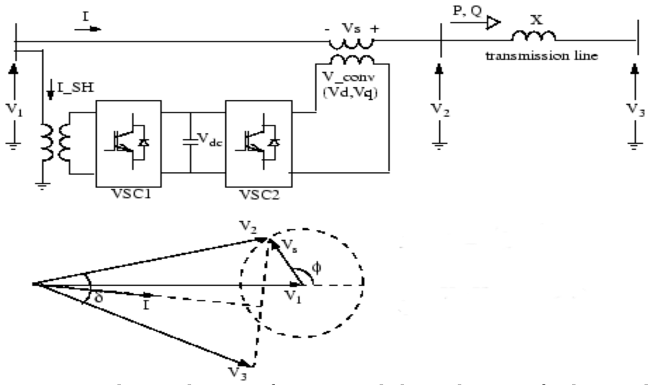


Fig. 10 Single Line diagram of a UPFC and phasor diagram of voltage and current.

$$P = \frac{V_2 V_3 \sin\delta}{X}$$

$$Q = \frac{V_2 (V_2 - V_3 \cos\delta)}{X}$$

This FACTS topology provides much more flexibility than the SSSC for controlling the line active and reactive power because active power can now be transferred from the shunt converter to the series converter, through the DC bus. Contrary to the SSSC where the injected voltage Vs is constrained to stay in quadrature with line current I, the injected voltage Vs can now have any angle with respect to line current. If the magnitude of injected voltage Vs is kept constant and if its phase angle φ with respect to V_1 is varied from 0 to 360 degrees, the locus described by the end of vector V_2 ($V_2 = V_1 + V_S$) is a circle as shown in Figure 10 on the phasor diagram. As φ is varying, the phase shift δ between voltages V_2 and V_3 at the two line ends also varies. It follows that both the active power P and the reactive power Q transmitted at one line end can be controlled.

VII. CLASSIFICATION OF FACTS CONTROLLERS

By considering five independent characteristics FACTS controllers are classified as follows:

- *Connection (S_1)*

IEEE groups FACTS controllers into three main categories based on how they are connected to AC power systems : 1) Series, 2) Shunt and 3) Combined series and shunt. Further these are divided into one-port and two-port connections, then it is subdivided into one-port series and parallel.
Connection = One-port, series (1S); One-port, parallel (1P); Two-port (2).

- *Commutation (S_2)*

Commutation can be either natural as with SCRs or it can be forced as with GTOs.
Commutation = Natural commutation (NC) ; or Forced commutation (FC).

❖ *Switching Frequency (S_3)*

Power systems have synchronous frequency of 50 Hz or 60 Hz, whereas the power electronics based systems can be operated over a wide range of switching frequencies.
Switching Frequency = low, $0 < f_s \leq f$ (LF); medium, $f < f_s \leq 10f$ (MF); high, $f_s > 10f$ (HF).

❖ *Energy Storage (S_4)*

Substantial Energy storage is required particularly for those controllers which absorb and deliver active power. In some other controllers, reactive power is generated and only active power that is associated with parasitic losses. Energy storage elements have to be able to provide transient overload capability for several cycles.
Energy storage = Zero energy storage (ZES); Capacitor energy storage (CES); Battery energy storage (BES); Superconducting energy storage (SES); or External energy storage (EES).

ZES	CES	BES	SES	EES	→
0	1	50	200,000		∞

❖ *DC port (S_5)*

The current FACTS controllers can also be divided into two groups according to the presence and absence of a dc port.
DC port = dc port employed (DC); or no dc port employed (NDC).

TABLE 4. SHUNT CONNECTED FACTS CONTROLLERS

TYPE - 1	SHUNT CONNECTED FACTS CONTROLLERS		
Names	Classification	Main Function	Subsidiary Function
SVC (Static VAR Compensator)	1P-NC-LF-ZES-NDC	Voltage Control	VAR Compensation, Steady state, Dynamic stability
STATCOM (Static Synchronous Compensator	1P-FC-HF-CES-DC	Voltage Control	VAR Compensation, Damping of Oscillation, Transient stability

TABLE 5. SERIES CONNECTED FACTS CONTROLLERS

TYPE - 2	SERIES CONNECTED FACTS CONTROLLERS		
Names	Classification	Main Function	Subsidiary Function
SSSC (Static Synchronous Series Compensator)	1S-FC-HF-CES-DC	Controlling transmitted electric power by increasing or decreasing reactive voltage drop while expecting no SSR effect	Increase or decrease resistive voltage drop across the transmission line to enhance dynamic behaviour
TCSC (Thyristor Controlled Series Compensator)	1S-NC-LF-NES-NDC	Capacitive/inductive reactance compensator in a continuous manner	

TABLE 6. TWO PORT FACTS CONTROLLERS

TYPE - 3	TWO PORT FACTS CONTROLLERS		
Names	Classification	Main Function	Subsidiary Function
UPFC (Unified Power Flow Controllers)	2-FC-HF-CES-DC	Terminal voltage control, phase angle regulation, series line compensation	VAR Compensation

VIII. FACTS TECHNOLOGY's BENEFITS

FACTS Devices enables the transmission system to obtain one or more following benefits:

- Main function of FACTS devices is to control power flow. The use of power flow control may be to follow a contract, meet the utilities' own needs, ensure optimum power flow, ride through emergency conditions, or a combination of them.
- Increase utilization of lowest cost generation. One of the principal reasons for transmission interconnections is to utilize the lowest cost generation. When this cannot be done, it follows that there is not enough cost-effective transmission capacity. Cost-effective enhancement of capacity will therefore allow increased use of lowest cost generation.
- Distributed Generators enhancement.
- Increase the loading capability of lines to their thermal capabilities, including short term and seasonal demands.

- Increased system reliability.
- Elimination or deferral of the need for new transmission lines.
- Added flexibility in sitting new generation.
- Provide secure tie-line connections to neighbouring utilities and regions thereby decreasing overall generation reserve requirements on both sides.
- Upgrade of transmission lines.
- Increased system security.
- Reduce Reactive Power flows, thus allowing the lines to carry more Active Power.
- Loop flow control.
- Beneficial for Environment.

Table 7 below shows benefits of FACTS devices for different applications.

TABLE 7. BENEFITS OF FACTS DEVICES FOR DIFFERENT APPLICATIONS

FACTS Devices	**Voltage control**	**Transient stability**	**Dynamic stability**	**Load flow control**
SVC	***	*	**	*
STATCOM	***	**	**	*
TCSC	*	***	**	**
UPFC	***	***	***	***

Where * is Good, ** is Better, *** is Best

IX. APPLICATION OF FACTS CONTROLLERS

Following TABLE 8 shows the application of various FACTS controllers.

TABLE 8. APPLICATION OF FACTS CONTROLLERS

Issues	**Problem**	**Corrective Action**	**Conventional Solution**	**New Equipment (FACTS)**
Voltage Limits	Low voltage at heavy load	Supply RP	Shunt capacitor, Series capacitor	TCSC, STATCOM
	High voltage at heavy load	Remove RP supply	Switch EHV line and/or shunt capacitor	TCSC
		Absorb RP	Switch shunt capacitor, shunt reactor, SVC	STATCOM
	Low voltage following outage	Supply RP limit	Switch, shunt capacitor, reactor, SVC, switch series capacitor	STATCOM, TCSC
		Prevent over load	Series reactor, PAR	TCSC
	Low voltage and overload	Supply RP and limit over load	Combination of two or more equipment	UPFC, STATCOM
Thermal Limits	Line/ transformer overload	Reduce overload	Add line / transformer	TCSC, UPFC
	Tripping of parallel circuit	Limit circuit loading	----------------------	UPFC
Short circuit levels	Excessive breaker fault current	Limit short-circuit current	Add series reactor, fuses, new circuit breaker	UPFC

X. CONCLUSION

In this paper an attempt has been made to review various literatures for the introduction of various FACTS controllers such as SVC, TCSC, STATCOM, SSSC and UPFC. Also in this review article an attempt is made to find out possible benefits of these controllers and recent applications of the same. According to the proposed schemes existing FACTS controllers are being classified.

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