

INTRODUCTION TO FACTS CONTROLLERS A CRITICAL REVIEW

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ABSTRACT

This paper presents the introduction of various FACTS controllers such as SVC, TCSC, TCPAR or TCPAT, SSSC, STATCOM, UPFC, IPFC, GUPFC, HPFC for operation, control, planning & protection from different performance point of view such as increased the loadability, improve the voltage profile, minimize the active power losses, increased the available transfer capacity, enhance the transient and steady-state stability, and flexible operations of power systems. Also this paper presents the current status on the introduction of various FACTS controllers such as SVC, TCSC, TCPAR or TCPAT, SSSC, STATCOM, UPFC, IPFC, GUPFC, HPFC for operation, control, planning & protection from different performance point of view such as increased the loadability, improve the voltage profile, minimize the active power losses, increased the available transfer capacity, enhance the transient and steady-state stability, and flexible operations of power systems. Authors strongly believe that this article will be very much useful to the researchers for finding out the relevant references in the field of the various FACTS controllers for operation, control, planning & protection of power systems.

Keywords:-Flexible AC Transmission Systems (FACTS), FACTS Controllers, SVC, TCSC, TCPAR or TCPAT, SSSC, STATCOM, UPFC, IPFC, GUPFC, HPFC, Power Systems.

1. INTRODUCTION

The power flow over a transmission line depends mainly on three important parameters, namely voltage magnitude of the buses (V), impedance of the transmission line (Z) and phase angle between buses (θ). The FACTS devices control one or more of the parameters to improve system performance by using placement and coordination of multiple FACTS controllers in large-scale emerging power system networks to also show that the achieve significant improvements in operating parameters of the power systems such as small signal stability, transient stability, damping of power system oscillations, security of the power system, less active power loss, voltage profile, congestion management, quality of the power system, efficiency of power system operations, power transfer capability through the lines, dynamic performances of power systems, and the

loadability of the power system network also increased. As FACTS devices are fabricated using solid state controllers, their response is fast and accurate. Thus these devices can be utilized to improve the voltage profile of the system by using coordinated control of FACTS controllers in multi-machine power systems in this work.

A. Generation of FACTS Controllers:

The following generation of FACTS controllers for the development of FACTS controllers:

a. First Generation of FACTS Controllers:

The following FACTS controllers such as Static Var Compensator (SVC), Thyristor Controlled Series Capacitor (TCSC), and Thyristor Controlled Phase Shifting Transformer (TCPST) are

developed in the first generation of FACTS controllers.

b. Second Generation of FACTS Controllers:

The following FACTS controllers such as Static Synchronous Compensator (STATCOM), Static Synchronous Series Compensator (SSSC), Unified Power Flow Controller (UPFC), and Interline Power Flow Controller (IPFC) are developed in the second generation of FACTS controllers.

B. Concepts of FACTS Technology:

IEEE definition of FACTS and FACTS controllers are given as [1].

- **Flexible AC Transmission System (FACTS):** *Alternating current transmission systems incorporating power electronics based and other static controllers to enhance controllability and increase power transfer capability.*
- **FACTS Controller:** *Power electronics based system and other static equipment that provides control of one or more AC transmission system parameters.*

In general, FACTS controllers can be divided in following categories

- ❖ Series controllers such as Thyristor Controlled Series Capacitor (TCSC), Thyristor Controlled Phase Angle Regulators (TCPAR or TCPST), and Static Synchronous Series Compensator (SSSC)
- ❖ Shunt controllers such as Staic Var Compensator (SVC), and Static Synchronous Compensator (STATCOM)
- ❖ Combined series-series controllers such as Interline Power Flow Controller(IPFC)
- ❖ Combined series-shunt controllers such as Unified Power Flow Controller(UPFC)

In this thesis we shall concentrate only on the TCSC, SVC, STATCOM, and UPFC devices. A brief review of series, shunt, series-series, and series-shunt devices such as TCSC, TCPAR or TCPST, SSSC, SVC, STATCOM, IPFC, and UPFC, GUPFC, HPFC are presented in below.

This paper is organized as follows: Section II discusses the introduction to various FACTS controllers. Section III presents the results and discussion of the problem. Section IV presents the conclusions of the paper.

2. INTRODUCTION TO VARIOUS FACTS CONTROLLERS

A. Thyristor Controlled Series Capacitor (TCSC) [1]-[18]

A 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 [1].

Even through a TCSC in the normal operating range in mainly capacitive, but it can also be used in an inductive mode. The power flow over a transmission line can be increased by controlled series compensation with minimum risk of sub-synchronous resonance (SSR) [1]. TCSC is a second generation FACTS controller, which controls the impedance of the line in which it is connected by varying the firing angle of the thyristors. A TCSC module comprises a series fixed capacitor that is connected in parallel to a thyristor controlled reactor (TCR) i. e. Shown in Fig.1. A TCR includes a pair of anti-parallel thyristors that are connected in series with an inductor. In a TCSC, a metal oxide varistor (MOV) along with a bypass breaker is connected in parallel to the fixed capacitor for overvoltage protection. A complete compensation system may be made up of several of these modules.

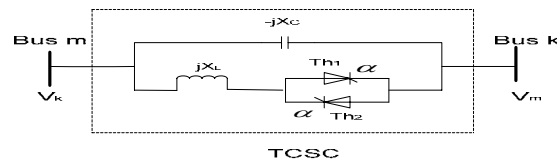


Fig. 1. TCSC module

The steady-state impedance of the TCSC is that of a parallel LC circuit, consisting of fixed capacitive impedance, X_c , and a variable inductive impedance, $X_L(\alpha)$, that is,

$$X_{TCSC}(\alpha) = \frac{X_c X_L(\alpha)}{X_L(\alpha) - X_c}$$

(1)

Where

$$X_L(\alpha) = X_L \frac{\pi}{\pi - 2\alpha - \sin 2\alpha}, X_L \leq X_L(\alpha) \leq \infty$$

(2)

$X_L = \omega L$, and α is the delay angle measured from the crest of the capacitor voltage (or, equivalently, the zero crossing of the line current). The impedance of the TCSC by delay is shown in Fig. 2.

The TCSC has three basic modes of operation

- ❖ *Thyristor valve bypass mode (inductive region operation: $0 \leq \alpha \leq \alpha_{Llim}$)*
- ❖ *Thyristor valve blocked mode (resonance region for inhibited operation: $\alpha_{Llim} \leq \alpha \leq \alpha_{Clim}$)*
- ❖ *Vernier control mode (capacitive region operation: $\alpha_{Clim} \leq \alpha \leq \pi/2$)*

1. *Thyristor valve bypass mode (inductive region operation: $0 \leq \alpha \leq \alpha_{Llim}$):* In the bypass mode thyristors are gated for full conduction and the current flow in the reactor is continuous and sinusoidal. In this case the net reactance is slightly inductive because the susceptance of reactor is larger than that of the capacitor. This mode is mainly used for protecting the capacitor against the overvoltage (during transient overcurrents in the line). In this mode of operation the behaviour of reactance of TCSC module as follows.

2. *Thyristor valve blocked mode (resonance region for inhibited operation: $\alpha_{Llim} \leq \alpha \leq \alpha_{Clim}$):* In the inserted mode with thyristor blocked, no current flows through the valve as the gate pulses are suppressed. In this mode, the TCSC reactance is the same as that the fixed capacitor. This mode is also termed as waiting mode. This mode is used to provide control and protective measures. The breaker is generally provided to remove TCSC from service when there are internal TCSC

failures. In this mode of operation the behaviour of reactance of TCSC module as follows.

3. *Vernier control mode (capacitive region operation: $\alpha_{Clim} \leq \alpha \leq \pi/2$):* In vernier control mode, thyristors are gated in such a manner that a controlled amount of inductive current can be circulate through the capacitor thereby increasing effective capacitive/inductive reactance of the module. In this mode of operation the behaviour of reactance of TCSC module as follows.

All the modes of operation (regions of operation) of TCSC are shown in Fig.2.2.

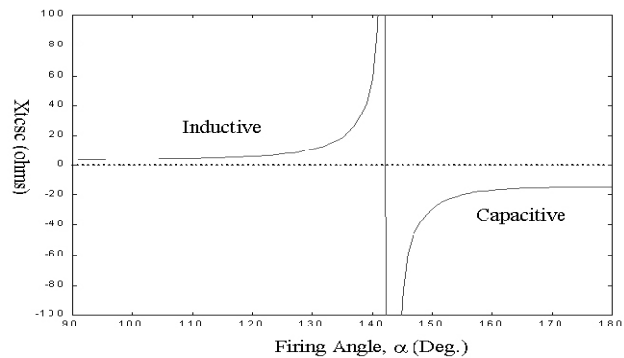


Fig.2. TCSC equivalent Reactance as a function of firing angle

4. *Explanations of above TCSC characteristics:* The TCSC thus presents a tunable parallel LC circuit to the line current that is substantially a constant alternating current source. As the impedance of the controlled reactor, $X_L(\alpha)$, is varied from its maximum (infinity) towards its minimum (ωL), the TCSC increases its minimum capacitive impedance, $X_{TCSCmin} = X_c = 1/\omega C$, (and thereby the degree of series capacitive compensation) until parallel resonance at $X_c = X_L(\alpha)$ is established and $X_{TCSCmax}$ theoretically becomes infinite. Decreasing $X_L(\alpha)$ further, the impedance of the TCSC, $X_{TCSC}(\alpha)$ becomes inductive, reaching its minimum value of $X_c X_L(\alpha) / X_L(\alpha) - X_c$ at $\alpha = 0$, where the capacitor is in effect bypassed by the TCR. Therefore, with the usual TCSC arrangement in which the impedance of the TCR reactor, X_L , is smaller than that of the capacitor, X_c , the TCSC has two operating ranges around its internal circuit resonance; one is the $\alpha_{Clim} \leq \alpha \leq \pi/2$ range,

where $X_{TCSC}(\alpha)$ is becomes capacitive, and the other is the $0 \leq \alpha \leq \alpha_{Lim}$ range, where $X_{TCSC}(\alpha)$ is inductive, as illustrated in figure .2. From above characteristics it is observed that TCSC can't work in a particular band of firing angle i.e. shown in above figure due to resonance phenomena occurs in TCSC in this zone. This is the drawback of TCSC operations in power systems.

5. *Installation of TCSC device:* Initial experience with TCSC installation has been favourable. A TCSC has been installed on the American Electric Power (AEP) 345 kV system in 1991 and another on the Western Area Power Administration (WAPA) 230 kV system in northeastern Arizona at the Kayenta substation in 1992. A third TCSC has been connected to the BPA 500 kV system at Slatt in 1993 for power flow control and improvement of system performance.

B. Thyristor Controlled Phase Angle Regulators (TCPAR) [19]

The TCPAR is equipment that can control power flow in transmission lines of power system by regulating the phase angle of the bus voltage. Environment restrictions usually restrict opportunities of reinforcement through the consideration of new routes. In such a situation, Flexible AC Transmission System (FACTS) controllers such as TCPAR play an important role in increasing loadability of the existing system and controlling the congestion in the network.

FACTS device like TCPAR can be used to regulate the power flow in the tie-lines of interconnected power system. When TCPAR is equipped with power regulator and frequency based stabiliser it can also significantly influence the power flow in the transient states occurring after power disturbances. In the case of simple interconnected power system, consisting of two power systems the control of TCPAR can force a good damping of both power swings and oscillations of local frequency. In the case of larger interconnected power system consisting of more than two power systems the influence of the control of TCPAR on damping can be more complicated. Strong damping of local frequency oscillations and power swings in one tie-line may cause larger oscillations in remote tie-lines and other systems. Hence using devices like TCPAR as a tool for damping of power swings

and frequency oscillations in a large interconnected power system must be justified by detailed analysis of power system dynamics.

The power injection model of TCPAR is shown in Fig.3.

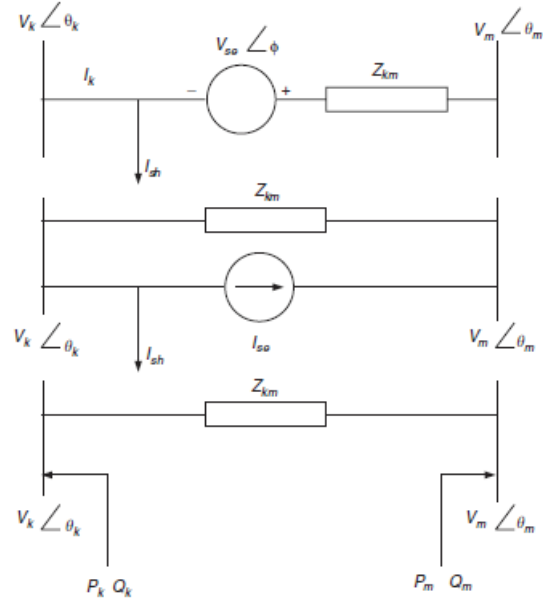


Fig. 3. Power injection model of TCPAR

C. Static Var Compensator (SVC) [20]-[44]

According to IEEE-CIGRE co-definition [1], a static var compensator is a static var generator whose output is varied so as to maintain or control specific parameters (e.g. voltage or reactive power of bus) of the electric power system.

SVC is a first generation FACTS controller that is already in operation at various places in the world. In its simplest form it uses a thyristor controlled reactor (TCR) in conjunction with a fixed capacitor (FC) or thyristor switched capacitor (TSC). A pair of opposite poled thyristors is connected in series with a fixed inductor to form a TCR module while the thyristors are connected in series with a capacitor to form a TSC module. An SVC can control the voltage magnitude at the required bus thereby improving the voltage profile of the system. The primary task of an SVC is to maintain the voltage of a particular bus by means of reactive power compensation (obtained by varying the firing angle of the thyristors). It can also provide increased damping to power oscillations and enhance power flow over a line by using auxiliary

signals such as line active power, line reactive power, line current, and computed internal frequency.

Static VAR Compensator (SVC) is a shunt connected FACTS controller whose main functionality is to regulate the voltage at a given bus by controlling its equivalent reactance. Basically it consists of a fixed capacitor (FC) and a thyristor controlled reactor (TCR). Generally they are two configurations of the SVC i.e. shown in Fig. 4.(a)&(b)

1. *SVC total susceptance model:* A changing susceptance B_{svc} represents the fundamental frequency equivalent susceptance of all shunt modules making up the SVC as shown in Fig. 4.(a).

2. *SVC firing angle model:* The equivalent reactance X_{SVC} , which is function of a changing firing angle α , is made up of the parallel combination of a thyristor controlled reactor (TCR) equivalent admittance and a fixed capacitive reactance as shown in Fig. 4. (b).

This model provides information on the SVC firing angle required to achieve a given level of compensation.

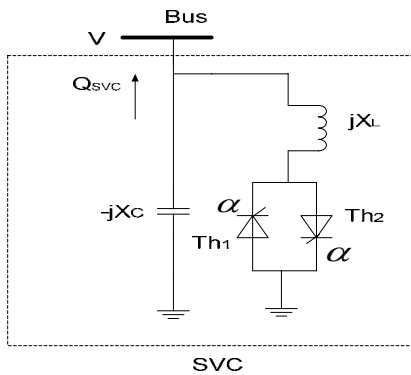


Fig. 4. (a) SVC firing angle model

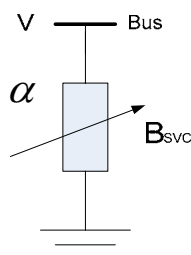


Fig. 4. (b) SVC total susceptance model

Figure 5 shows the steady-state and dynamic voltage-current characteristics of the SVC. In the

active control range, current/susceptance and reactive power is varied to regulate voltage according to a slope (droop) characteristic. The slope value depends on the desired voltage regulation, the desired sharing of reactive power production between various sources, and other needs of the system. The slope is typically 1-5%. At the capacitive limit, the SVC becomes a shunt capacitor. At the inductive limit, the SVC becomes a shunt reactor (the current or reactive power may also be limited).

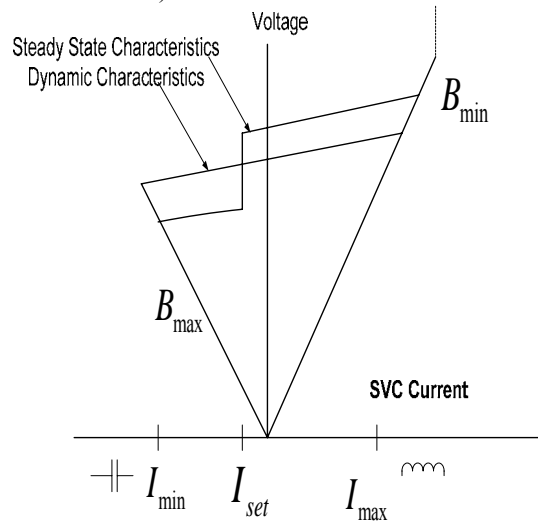


Fig.5. steady-state and dynamic voltage/current Characteristics of the SVC

SVC firing angle model is implemented in this paper. Thus, the model can be developed with respect to a sinusoidal voltage, differential and algebraic equations can be written as

$$I_{SVC} = -jB_{SVC}V_k$$

(3)

The fundamental frequency TCR equivalent reactance X_{TCR}

$$X_{TCR} = \frac{\pi X_L}{\sigma - \sin \sigma}$$

(4)

Where $\sigma = 2(\pi - \alpha)$, $X_L = \omega L$

And in terms of firing angle

$$X_{TCR} = \frac{\pi X_L}{2(\pi - \alpha) + \sin 2\alpha}$$

(5)

σ and α are conduction and firing angles respectively.

At $\alpha = 90^\circ$, TCR conducts fully and the equivalent reactance

XTCR becomes XL, while at $\alpha = 180^\circ$, TCR is blocked and its equivalent reactance becomes infinite.

The SVC effective reactance X_{SVC} is determined by the parallel combination of X_C and X_{TCR}

$$X_{SVC}(\alpha) = \frac{\pi X_C X_L}{X_C [2(\pi - \alpha) + \sin 2\alpha] - \pi X_L}$$

(6)

Where $X_C = 1/\omega C$

$$Q_k = -V_k^2 \left\{ \frac{X_C [2(\pi - \alpha) + \sin 2\alpha]}{\pi X_C X_L} \right\}$$

(7)

The SVC equivalent reactance is given above equation. It is shown in Fig. that the SVC equivalent susceptance

$$(B_{SVC} = -1/X_{SVC})$$

profile, as function of firing angle, does not present discontinuities, i.e., B_{SVC} varies in a continuous, smooth fashion in both operative regions. Hence, linearization of the SVC power flow equations, based on B_{SVC} with respect to firing angle, will exhibit a better numerical behavior than the linearized model based on X_{SVC} . In SVC, the resonance phenomenon is present as similar to TCSC. So, this device cant operated in a particular zone due these phenomena. This is the drawback of SVC operations in power systems. Figure 6. Shows the SVC equivalent susceptance profile.

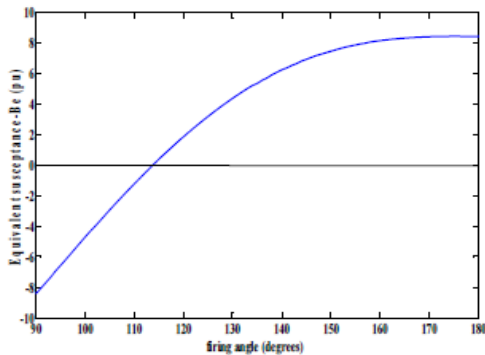


Fig.6. SVC equivalent susceptance profile

D. Static Synchronous Series Compensator (SSSC) [45]-[48]

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 behaviour of the power system by additional temporary real power compensation, to increase or decrease momentarily, the overall real voltage drop across the line [1].

An SSSC incorporates a solid state voltage source inverter that injects an almost sinusoidal voltage of variable magnitude in series with a transmission line. The SSSC has the same structure as that of a STATCOM except that the coupling transformer of an SSSC is connected in series with the transmission line. The injected voltage is mainly in quadrature with the line current. A small part of injected voltage, which is in phase with the line current, provides the losses in the inverter. Most of injected voltage, which is in quadrature with the line current, emulates a series inductance or a series capacitance thereby altering the transmission line series reactance. This emulated reactance, which can be altered by varying the magnitude of injected voltage, favourably influences the electric power flow in the transmission line. The structure of SSSC shown in Fig.7.

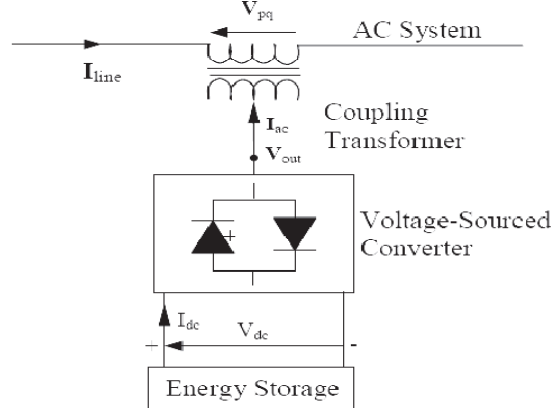


Fig. 7. The basic structure of Static synchronous series compensator (SSSC)

SSSC is a solid-state synchronous voltage source employing an appropriate DC to AC inverter with gate turn-off thyristor. It is similar to the STATCOM, as it is based on a DC capacitor fed VSI that generates a three-phase voltage, which is then injected in a transmission line through a transformer connected in series with the system. In SSSC, the resonance phenomena has been removed. So SSSC is having more superior performance as compare to TCSC.

The main control objective of the SSSC is to directly control the current, and indirectly the power, flowing through the line by controlling the reactive power exchange between the SSSC and the AC system. The main advantage of this controller over a TCSC is that it does not significantly affect the impedance of the transmission system and, therefore, there is no danger of having resonance problem.

E. Static Synchronous Compensator (STATCOM) [49]-[50]

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 [1].

A STATCOM is a solid state switching converter capable of generating or absorbing independently controllable real and reactive power at its output terminals, when it is fed from an energy source or an energy storage device of appropriate rating. A STATCOM incorporate a voltage source inverter (VSI) that produces a set of three phase ac output voltages, each of which is in phase with, and coupled to the corresponding ac system voltage via a relatively small reactance. This small reactance is usually provided by the per phase leakage reactance of the coupling transformer. The VSI is driven by a dc storage capacitor. By regulating the magnitude of the output voltage produced, the reactive power exchange between STATCOM and the ac system can be controlled.

The Static Synchronous Compensator (STATCOM) is a power electronic-based Synchronous Voltage Generator (SVG) that generates a three-phase voltage from a dc capacitor in synchronism with the transmission line voltage and is connected to it by a coupling transformer as shown in Fig. 8. By controlling the magnitude of the STATCOM voltage, V_s , the reactive power exchange between the STATCOM and the transmission line and hence the amount of shunt compensation can be controlled.

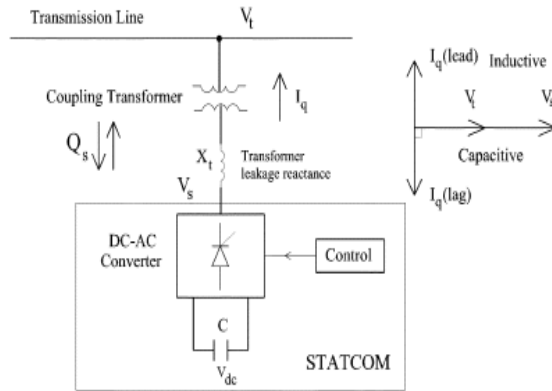


Fig. 8. The structure of Static synchronous compensator (STATCOM)

Figs.8 and 9 show the schematic diagram and terminal characteristic of STATCOM, respectively. From Fig. 8, STATCOM is a shunt-connected device, which controls the voltage at the connected bus to the reference value by adjusting voltage and angle of internal voltage source. From Fig.2.2.2.2, STATCOM exhibits constant current characteristics when the voltage is low/high under/over the limit. This allows STATCOM to deliver constant reactive power at the limits compared to SVC.

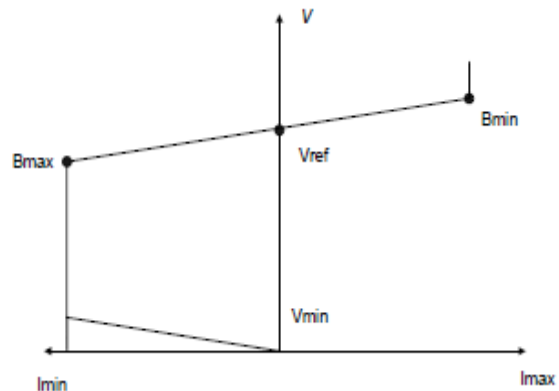


Fig. 9. Terminal characteristic of STATCOM.

The following mode of operation of STATCOM given as:

- 1. Over excited mode of operation ($V_o \geq V_{bus}$): That is, if the amplitude of the output voltage is increased above that of the ac system voltage, then the current flows through the reactance from the STATCOM to the ac system and the STATCOM generates reactive (capacitive) power for the ac system.

2. Under excited mode of operation ($V_o \leq V_{bus}$): On the other hand, if the amplitude of the output voltage is decreased below that of the ac system, then the reactive current flows from the ac system to STATCOM, and the STATCOM absorbs the reactive (inductive) power.

3. Normal (floating) excited mode of operation ($V_o = V_{bus}$): If the output voltage is equal to the ac system voltage, the reactive power exchange is zero.

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

F. Unified Power Flow Controller(UPFC)[51]-[77]

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 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 is the most versatile and powerful FACTS device. UPFC is also known as the most comprehensive multivariable flexible ac transmission system (FACTS) controller. Simultaneous control of multiple power system variables with UPFC poses enormous difficulties. In addition, the complexity of the UPFC control increases due to the fact that the controlled and the variables interact with each other. The Unified Power Flow Controller (UPFC) is used to control the power flow in the transmission systems by controlling the impedance, voltage magnitude and phase angle. This controller offers advantages in terms of static and dynamic operation of the power system. It also brings in new challenges in power electronics and power system design. The basic structure of the UPFC consists of two voltage

source inverter (VSI); where one converter is connected in parallel to the transmission line while the other is in series with the transmission line.

The UPFC consists of two voltage source converters; series and shunt converter, which are connected to each other with a common dc link. Series converter or Static Synchronous Series Compensator (SSSC) is used to add controlled voltage magnitude and phase angle in series with the line, while shunt converter or Static Synchronous Compensator (STATCOM) is used to provide reactive power to the ac system, beside that, it will provide the dc power required for both inverter. Each of the branches consists of a transformer and power electronic converter. These two voltage source converters shared a common dc capacitor. The energy storing capacity of this dc capacitor is generally small. Therefore, active power drawn by the shunt converter should be equal to the active power generated by the series converter. The reactive power in the shunt or series converter can be chosen independently, giving greater flexibility to the power flow control. The coupling transformer is used to connect the device to the system. Figure .10. Shows the schematic diagram of the three phases UPFC connected to the transmission line.

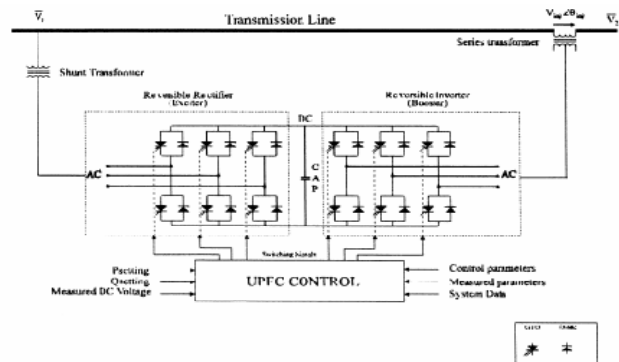


Figure 10. Schematic diagram of three phases UPFC connected to a transmission line

With the presence of the two converters, UPFC not only can supply reactive power but also active power. Figure 11 and 12 shows the equivalent single line circuit diagram representation of UPFC in power system and UPFC model schematic. The figure 13 shows the UPFC model equivalent.

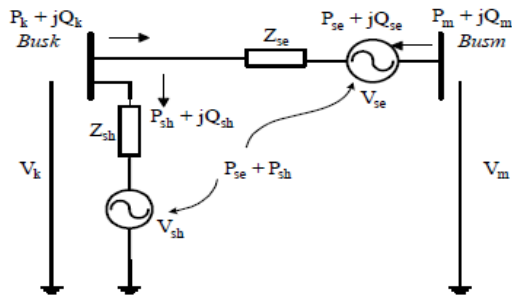


Figure 11 Equivalent single line circuit diagram representation of UPFC in power systems

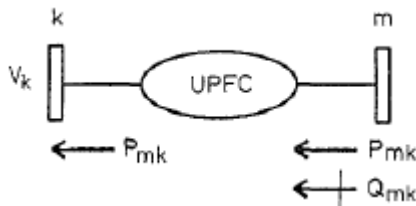


Fig.12 UPFC model schematic

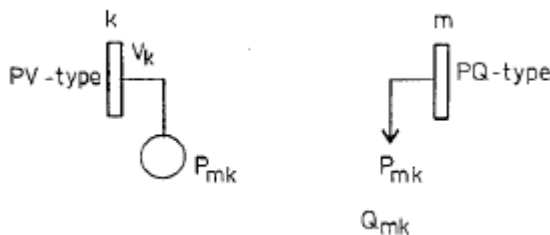


Fig.13 UPFC model equivalent

The sending end of the UPFC is transformed into a PQ bus, whilst the receiving end is transformed into a PV bus. The active and reactive power loads in the PQ bus are set to the values being controlled by the UPFC. The voltage magnitude at the PV bus is set at the value to be controlled by the UPFC. A standard load flow solution is carried out with the equivalent model given in Fig. 5. After load flow convergence, an additional set of nonlinear equations is solved by iteration to compute the UPFC parameters. This method is simple but will only work if the UPFC is used to control voltage magnitude, active power and reactive power, simultaneously. If one only wishes to control one or two variables, the method is no longer applicable. Moreover, since the UPFC parameters are computed after the load flow has converged, there is no way of knowing during the iterative process whether or not the UPFC parameters are within limits.

G. Interline Power Flow Controller (IPFC) [78]-[81]

Generally, the Interline Power Flow Controller (IPFC) is a combination of two or more independently controllable static synchronous series compensators (SSSC) which are solid-state voltage source converters which inject an almost sinusoidal voltage at variable magnitude and couples via a common DC link as shown in Figure 1. Conventionally, series capacitive compensation fixed, thyristor controlled or SSSC based, is employed to increase the transmittable real power over a given line and to balance the loading of a normally encountered multi-line transmission system. They are controlled to provide a capability to directly transfer independent real power between the compensated lines while maintaining the desired distribution of reactive flow among the line. The figure 14 and 15 shows the Simplified schematic of two-converter IPFC model and basic Two-Inverter Interline Power Flow Controller respectively.

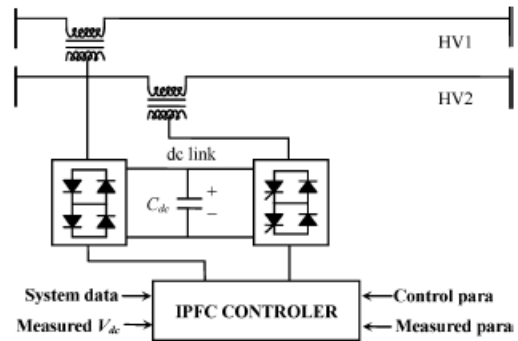


Fig.14. Simplified schematic of two-converter IPFC model

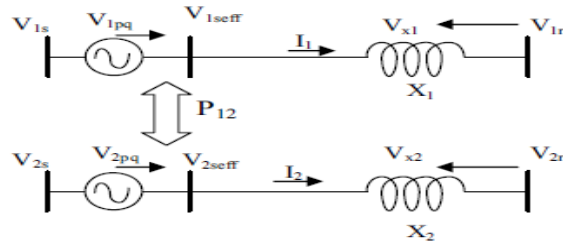


Fig. 15. Basic Two-Inverter Interline Power Flow Controller.

The figure 16 and 17 shows the equivalent circuit diagram of the IPFC and power injection model of two converters IPFC respectively.

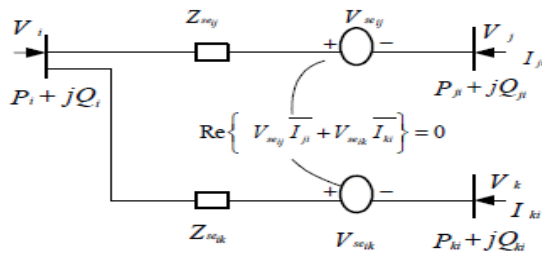


Fig. 16. Equivalent Circuit diagram of the IPFC

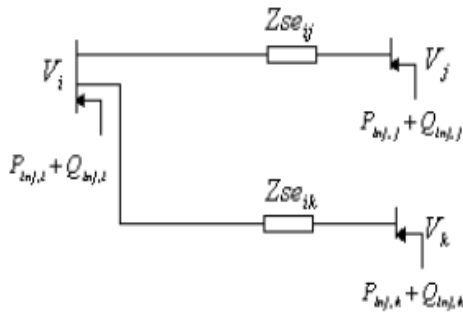


Fig. 17. Power injection model of two converters IPFC

H. Generalized Unified Power Flow Controller (GUPFC) [82]-[84]

1. *Operating Principles of GUPFC:*

An innovative approach to utilization of FACTS controllers providing a multifunctional power flow management device. There are several possibilities of operating configurations by combing two or more converter blocks with flexibility. Among them, there are two novel operating configurations, namely the Interline Power Flow Controller (IPFC) and the Generalized Unified Power Flow Controller (GUPFC), which are significantly extended to control power flows of multi-lines or a sub-network rather than control power flow of single line by a Unified Power Flow Controller (UPFC) or Static Synchronous Series Compensator (SSSC).

In contrast to the practical applications of the GUPFC in power systems, very few publications have been focused on the mathematical modeling of this new FACTS controller in power system analysis. A fundamental frequency model of the GUPFC consisting of one shunt converter and two series converters for EMTP study was proposed quite recently in open literatures. While modeling the GUPFC in power flow, optimal power flow

(OPF) analysis has not been reported yet. Therefore, in open literatures, a mathematical model of the GUPFC suitable for power flow and optimal power flow study is established. In the past three decades, techniques such as Newton method, sequential linear and quadratic programming method, PQ de-coupling method, etc. Have been used to solve optimal power flow problems.

The GUPFC with combing three or more converters working together extends the concepts of voltage and power flow control beyond what is achievable with the known two-converter UPFC FACTS controller [1], [2]. The simplest GUPFC consists of three converters, one connected in shunt and the other two in series with two transmission lines in a substation [5]. It can control total five power system quantities such as a bus voltage and independent active and reactive power flows of two lines. Such a GUPFC, which is shown in Fig. 18, is used to show the basic operation principle for the sake of simplicity. However, the mathematical derivation is applicable to a GUPFC with an arbitrary number of series converters.

In the steady state operation, the main objective of the GUPFC is to control voltage and power flow. The equivalent circuit of the GUPFC consisting of one controllable shunt injected voltage source and two controllable series injected voltage sources is shown in Fig. 19. Real power can be exchanged among these shunt and series converters via the common DC link. The sum of the real power exchange should be zero if we neglect the losses of the converter circuits. For the GUPFC shown in Figs. 18 and 19, it has total 5 degrees of control freedom, which means it can control five power system quantities such as one bus voltage, and 4 active and reactive power flows of two lines. It can be seen that with more series converters included within the GUPFC, more degrees of control freedom can be introduced and hence more control objectives can be achieved.

The simplest GUPFC consists of three switching converters. These converters are operated from two common dc link provided by two dc storage capacitors as shown in Fig. 18.

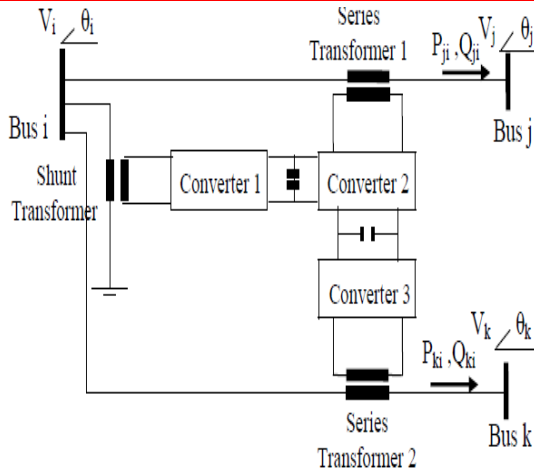


Fig. 18: Basic circuit arrangement of GUPFC

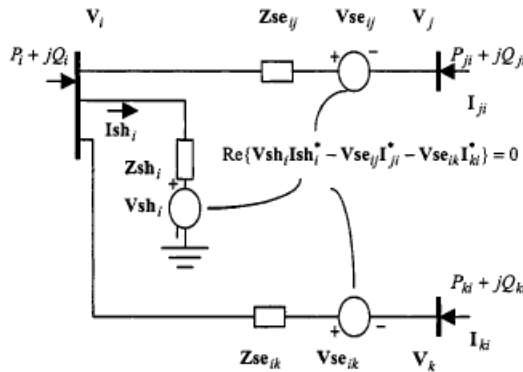


Fig. 19. The equivalent circuit of the GUPFC

I. Hybrid Power Flow Controllers (HPFC)[85]

In [1], introduced a hybrid flow controller (HFC) as a new member of flexible ac transmission system (FACTS) controllers for steady-state and power-flow control of power transmission lines. HFC is a hybrid compensator (i.e., provides series and/or shunt compensation). Structurally, an HFC unit is composed of a mechanically switched phase-shifting transformer, a mechanically switched shunt capacitor, and multi-module, series-connected, thyristor-switched capacitors and inductors. In [1], described the steady-state operation, single-phase equivalent circuit, power-flow model, and $V-I$ and $P-Q$ characteristics of the HFC. In [1], highlighted the steady-state technical features of the HFC for power-flow control of a study system and also provides a quantitative comparison of the HFC, UPFC, and PST.

In [1], introduced a hybrid flow controller (HFC) as a new FACTS controller and: 1) describes its steady-state principles of operations; 2) develops

its single-line equivalent circuit and power-flow model; and 3) investigates its steady-state power-flow control characteristics. Conceptually, HFC is not a new circuit configuration and rather an amalgamation of existing and well established power-flow controllers, that is,

- conventional mechanically switched phase-shifting transformer (PST);
- a conventional mechanically switched shunt capacitor (MSC);
- a multi-module thyristor-switched series capacitor (TSSC);
- a multi-module thyristor-switched series reactors (TSSR).

TSSC and TSSR subsystems of an HFC are electronically switched, and thus are adequately fast to 1) respond to system dynamics and 2) provide dynamic power-flow control. However, this paper investigates only steady-state behavior and characteristics of an HFC. Due to the inherent discrete operational nature of the HFC, its dynamic control and behavior are best investigated based on a discrete-event supervisory control strategy and will be the subject of a separate article.

HFC belongs to the family of hybrid compensators since it provides power-flow control through series and/or shunt compensation, analogous to the unified power-flow controller (UPFC). Although HFC does not offer all versatility and technical features of the UPFC, its salient features make it an alternative to the UPFC. These features are:

- cost effectiveness;
- simplicity of concept, control, and operational strategies;
- maturity and ruggedness of the technologies of its various subsystems;
- lower losses and, thus, higher efficiency.

HFC provides economical incentive in a scenario that an existing PST is augmented with TSSC and/or TSSR modules to form an HFC. Furthermore, since TSSC and TSSR modules are not phase-controlled and only switched in and out by thyristor switches, HFC does not generate harmonics and has no adverse impact on power quality.

1. Principles Of Operations Of HPFC:

Fig. 1 shows a schematic diagram of an HFC that is connected between buses i and j within a transmission line and is comprised of:

- a PST which can inject a lead/lag, quadrature-phase voltage;
- multimodule TSSC system that can insert a variable series capacitive reactance, in discrete steps, to adjust the line series reactance;
- multimodule TSSR system that can insert a variable series inductive reactance, in discrete steps, to prevent overflow;
- an MSC for reactive power compensation.

Due to their inherent large time-constants, PST and MSC can only impact steady-state power flow, while the TSSC and the TSSR modules can provide both dynamic and steady-state power-flow control. By replacing one TSSC module with a thyristor-controlled series capacitor (TCSC) module, continuous control of series reactance also can be achieved.

Based on the configuration of Fig. 20, a per-phase schematic representation of the HFC is given in Fig. 21. The details to reduce the single-phase PST of Fig. 2 from that of Fig. 1, under balanced conditions. The extraction of per phase representations of the TSSC, TSSR, and MSC of Fig. 2 from those of Fig. 20, under a balanced condition.

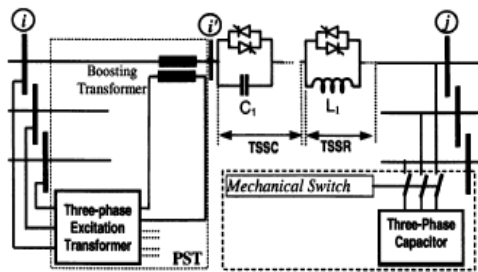


Fig. 20. Schematic diagram of an HPFC.

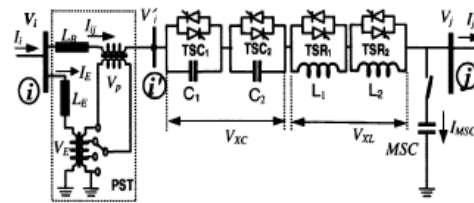


Fig. 21. Per-phase schematic representation of HPFC.

2. Steady-state $V-I$ characteristic of HPFC:

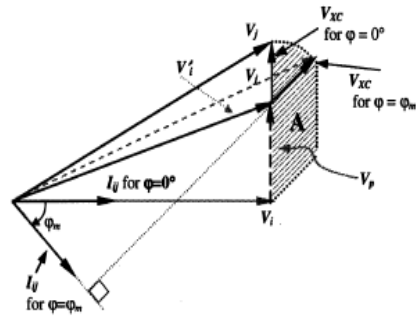
A steady-state $V-I$ characteristic of the HFC of Fig. 2 is shown in Fig. 3. V_i and V_j voltage phasors of buses i and j , respectively. The PST injects quadrature-phase voltage V_p , and V_i' is the voltage of the HFC internal bus (i.e., i' bus) (Fig. 2).

A steady-state $V-I$ characteristic of the HFC of Fig. 2 is shown in Fig. 3. V_i and V_j are voltage phasors of buses i and j , respectively. The PST injects quadrature-phase voltage V_p , and V_i' is the voltage of the HFC internal bus (i.e., bus i') (Fig. 2). In Fig. 3(a), the phasor of line current I_{ij} is lagging V_i by angle ϕ . Fig. 3(a) also shows the TSSC voltage V_{xc} for $\phi = 0^\circ$ and, $\phi = \phi_m$, and the corresponding voltage at bus j (i.e., V_j), corresponding to a pre-specified reactance of MSC. Magnitude of V_{xc} depends on 1) the magnitude of line current I_{ij} and 2) the number of TSSC modules in service.

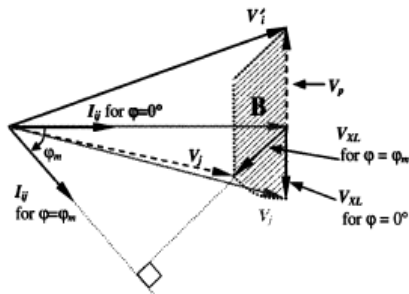
It should be noted that the TSSC is less effective to control real power flow when the line current is small. However the magnitude of the injected voltage by the PST is almost independent of the line current and can be controlled only by the PST voltage ratio, from 0 to V_{pmax} . As a result, for those conditions where the HFC operates under a lightly loaded line, the PST subsystem of HFC can effectively control real power flow, and the TSSC modules can be used to adjust the power flow only in small steps. Under heavy power-flow conditions, TSSC can effectively control the power flow and also reduce adverse impact of high current switching on the PST mechanical taps.

The Fig. 22(a) & (b) shows the steady-state V-I characteristics of HPFC.

analysis, nor for efficient storage. The power flow model of HPFC shown in fig. 23.



(a)



(b)

Fig. 22. Steady-state V - I characteristic of HPFC, (a) TSSC in service. (b) TSSR in service.

Fig. 3(b) shows a $V - I$ characteristic of the HFC when the TSSC modules are shorted and the TSSR is operational. Fig. 3(b) shows TSSR voltage phasor V_{XL} for $\varphi = 0^\circ$ and, $\varphi = \varphi_m$, and the corresponding a V_j bus j . A combination of shaded areas A and D of Fig. 22 specifies the - area that the HFC can control the line power flow. If the PST is capable of injecting lagging quadrature voltage, the corresponding $V - I$ characteristics regions are added to regions A and B of Fig. 3 to determine the overall $V - I$ area.

3. Power-flow model of HPFC:

Conceptually, there are three approaches to develop an HFC model for power-flow analysis. The first one is the classical approach which is based on augmenting the system matrix to include the HFC model. The drawback of this approach is that the augmented becomes asymmetrical, and thus can be used neither in a decoupled power-flow

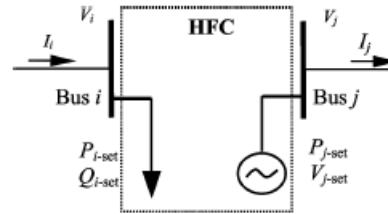


Fig. 23. Power-flow model of HPFC.

3. CONCLUSIONS

This paper presents the introduction of various FACTS controllers such as SVC, TCSC, TCPAR or TCPAT, SSSC, STATCOM, UPFC, IPFC, GUPFC, HPFC for operation, control, planning & protection from different performance point of view such as increased the loadability, improve the voltage profile, minimize the active power losses, increased the available transfer capacity, enhance the transient and steady-state stability, and flexible operations of power systems. Also this paper presents the current status on the introduction of various FACTS controllers such as SVC, TCSC, TCPAR or TCPAT, SSSC, STATCOM, UPFC, IPFC, GUPFC, HPFC for operation, control, planning & protection from different performance point of view such as increased the loadability, improve the voltage profile, minimize the active power losses, increased the available transfer capacity, enhance the transient and steady-state stability, and flexible operations of power systems.

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