**Recent Studies of FACTS devices for Power Flow Control**

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**Abstract –** World is facing acute power shortage for the past few years. As the population is increasing, this problem is becoming even worse so there is no option left but to increase our generation which is time demanding. FACTS controllers offers a new solution to this problem by improving transmission line capacities. FACTS controllers are basically power electronic based devices that offer an opportunity to enhance controllability, stability and power transfer capability of the transmission systems. This paper provides a comprehensive study of FACTS devices for power flow control.

***Keywords*:** Flexible AC Transmission System (FACTS), FACTS Controllers, Power Transmission, Power Flow Control, Power Electronics, Modern Power Systems, Electricity Markets.

I.INTRODUCTION

Modern power system is a complex network comprising of numerous generators, transmission lines, variety of loads and transformers. As a consequence of increasing power demand, some transmission lines are more loaded than was planned when they were built. With the increased loading of long transmission lines, the problem of transient stability after a major fault can become a transmission limiting factor [1]. Limitations on power transfer can always be relieved by the addition of new transmission lines and generation facilities. Alternatively, flexible alternating current transmission system (FACTS) controllers can enable the same objectives to be met with no major alterations to power system layout [2]. Main objectives of FACTS controllers are ensuring power flow in prescribed directions, secure loading of transmission lines, prevention of outages of healthy lines and damping of oscillations that can limit the usable line capacity[2]. These devices not only have the capability in controlling active and reactive power flow in an electrical network but also can redistribute power flow even under highly loaded condition that ultimately have the effect in reducing overall congestion [3]. Due to FACTS devices, the power can be flown through the chosen routes with consideration to mitigate the loss thereby averting losses due system tripping or outages. FACTS controllers have been in use in utilities around the world since 1970s, when the first utility demonstration of first family of FACTS named as Static VAR Compensator (SVC) was accomplished [4]. Since then the large effort was put in research and development of FACTS controllers. FACTS devices are classified as series, shunt, and various combinations of series and shunt controllers. Shunt controllers inject current whereas series controllers inject voltage in series at the point of connection. Recent Studies have shown that shunt and series compensation can be used to increase the maximum transfer capabilities of power networks [5]. FACTS controllers based on thyristor controlled reactors (TCRs), such as Static Var Compensators (SVCs) and Thyristor Controlled Series Capacitors (TCSCs), are being used by several utilities to compensate their system. It is well known fact that the Shunt compensation is basically reactive power compensation. Traditionally Shunt capacitors having advantage of less cost of maintenance and installation were used for shunt compensation. But shunt capacitors have the problem of poor voltage regulation and, beyond a certain level of compensation a stable operating point is unattainable. SVC is a shunt connected static Var generator whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific power system variables. In the limit of minimum or maximum suspectance SVC behaves like a fixed capacitor or an inductor. Choosing appropriate size is one of the major issues in SVC applications in voltage stability enhancement. Static Synchronous Compensator STATCOM is a voltage-source converter based device, which converts a DC input voltage into an AC output voltage in order to compensate the active and reactive power needs of the system [6] . STATCOM has better characteristics than SVC; when the system voltage drops sufficiently to force the STATCOM output to its ceiling, its maximum reactive power output will not be affected by the voltage magnitude. Series FACTS devices like TCSC are considered one such technology that reduces the transmission congestion and allows better utilization of the existing grid infrastructure, along with many other benefits[7]. A unified power flow controller (UPFC) is a versatile controller in the FACTS concept. It has the ability to adjust the three control parameters: the bus voltage, transmission line reactance, and phase angle between two buses, either simultaneously or independently. The inter-line power flow(IPFC) controller employs DC-to-AC converters each providing series compensation for different lines or buses. IPFC further extends the capability of independently influencing the active and reactive power flows to simultaneous compensation of multiple transmission lines. FACTS provide reactive power compensation between the lines. IPFC allows the power transfer from one line to the other. Some issues associated with the use of FACTS devices are proper location, appropriate size and setting, cost, modeling and controller interactions. The placing of controllable power system devices, such as the high voltage dc (HVDC) links and the flexible ac transmission system (FACTS) devices, is based on the issues unrelated to the damping of oscillations in the system[8]. Some of the FACTS devices are also used in damping the inter area oscillations. Power System Stabilizers are less effective for inter-area mode damping as compared to FACTS devices because the former require phase-lead design with reduced gain margin [9]. Placing appropriate FACTS device at suitable location with proper sizes leads to maximum loading of the transmission lines [10].

II. LITERATURE REVIEW

In [1] authors investigated the improvement of transient stability of a two-area power system, using UPFC (Unified Power Flow Controller) which is an effective FACTS (Flexible AC Transmission System) device capable of controlling the active and reactive power flows in a transmission line by controlling appropriately its series and shunt parameters. The Author also compared the performance of UPFC with other FACTS devices such as Static Synchronous Series Compensator (SSSC), Thyristor Controlled Series Capacitor (TCSC), and Static VAR Compensator (SVC) respectively. In [2] author provided a comprehensive review and evaluation of FACTS controllers. FACTS is a new technology based on power electronics, offers an opportunity to enhance controllability, stability and power transfer capability of ac transmission systems. In [3] author presented the application of Genetic Algorithm (GA) and Differential Evolution (DE) technique for the minimization of transmission loss and simultaneous reduction in the operating cost of the system using FACTS devices. Author had also proved that optimal placement of FACTS devices in the heavily loaded power system reduces transmission loss, control reactive power flow, improves voltage profile of all nodes and also reduces operating cost. It had been shown that system was reactively loaded starting from base to 200% of base reactive load and the system performance was observed without and with FACTS devices. The proposed technique was applied on IEEE 30-bus system for the optimal setting of FACTS devices. Finally, It was illustrated that how system performance is improved with the use of UPFC along with other series and shunt FACTS controller. In [4] author presented various facts related to the landmark development, practical installations, benefits and application of FACTS controllers in the electric utilities .Then the author presented comprehensive collection of major FACTS installations around the world. The work benefit that can be achieved and cost associated with these devices were also analyzed. highlighted the problem of high losses of advanced FACTS controllers as compared to conventional counterpart and need to take into account of interaction among controllers in future power system. One real world example of each major FACTS controller was presented and analyzed in the paper.

In [5] author presented detailed steady-state models with controls of two Flexible AC Transmission System (FACTS) controllers, namely, Static Var Compensators (SVCs) and Thyristor Controlled Series Capacitors (TCSCs), to study their effect on voltage collapse phenomena in power systems. Based on results at the point of collapse, design strategies were proposed for these two controllers, so that their location, dimensions and controls can be optimally defined to increase system loadability. A European system was also used to illustrate the application of all proposed models and techniques. In [6] author compared the shunt capacitor, SVC and STATCOM in static voltage stability improvement. Various performance measures are compared under different operating system conditions for the IEEE 14 bus test system. Important issues related to shunt compensation, namely sizing and installation location, for exclusive load margin improvement are addressed. A methodology is also proposed to alleviate voltage control problems due to shunt capacitor compensation during lightly and heavily loaded conditions. In [7] this paper author proposed two new methodologies for the placement of series FACTS devices in deregulated electricity market to reduce congestion. Similar to sensitivity factor based method, the proposed methods form a priority list that reduces the solution space. The proposed methodologies were based on the use of LMP differences and congestion rent, respectively.. The proposed methodologies were tested and validated for locating TCSC in IEEE 14-, IEEE 30- and IEEE 57-bus test systems. Results obtained with the proposed methods are compared with that of the sensitivity method and with exhaustive OPF solutions. The objective of FACTS device placement can be either to minimize the total congestion rent or to maximize the social welfare. Results showed that the proposed methods are capable of finding the best location for TCSC installation, that suite both objectives. In [8] author proposed a method to select the input signals for both single and multiple flexible ac transmission system (FACTS) devices in small and large power systems. Different input output controllability analyses were used to assess the most appropriate input signals (stabilizing signal) for the static var compensator (SVC), the static synchronous compensator (SSSC), and the unified power-flow controller (UPFC) for achieving good damping of inter area oscillations. The study presented in this paper was carried out on one small system with one FACTS device at a time; and one large system equipped with the SVC, the SSSC, and the UPFC. In [9] author demonstrated the enhancement of inter-area mode damping by multiple flexible ac transmission systems (FACTS) devices. Power system damping control design was formulated as an output disturbance rejection problem. A 16-machine, five-area study system reinforced with a controllable series capacitor (CSC), a static var compensator (SVC), and a controllable phase shifter (CPS) at different locations was considered. The controllers designed for these devices were found to effectively damp out inter-area oscillations. The damping performance of the controllers was examined in the frequency and time domains for various operating scenarios. The controllers were found to be robust in the face of varying power-flow patterns, nature of loads, tie-line strengths, and system nonlinearities, including device saturations. In [10] author had compared FACTS devices for static voltage stability study. Various performance measures including PV curves, voltage profiles, and power losses were compared under normal and contingency conditions. Placement and sizing techniques of series FACTS devices and UPFC were proposed for loading margin enhancement. The paper provided a guide for utilities to have an appropriate choice of FACTS device for enhancing loading margin and static voltage stability.

III. MOTIVATION

World is facing acute power shortage for the past few years. As the population is increasing, this problem is becoming even worse so there is no option left but to increase our generation. But there is another problem. Transmission lines are already working at their full capacity, there are two options then:

* To install new transmission lines.
* To increase the power transfer capability of the already existing lines through FACTS controllers.

Increased cost of transmission lines and the difficulty to acquire new rights of way make FACTS indispensable. So there is a direct need to study the application of these devices on a small portion of electric network. All the reviewed work shows that Power Flow in electric power system is of prime concern. As we know that active power is directly related to the frequency and reactive power is a function of voltage. As the load increases bus voltage drops and can cross the minimum allowable limit. So the buses which are operating closer to the limits have a tendency to drop their voltage below 0.95p.u, which is a limiting standard. So there is a need of setting and maintaining a reference voltage level throughout the operation of a power system. Moreover, in case of contingency of one line others can become overloaded. We can maintain power flow across lines by fixing FACTS devices. They will only allow the reference power to flow, diverting the remaining power to flow from under-loaded lines.

IV. RECENT STUDIES OF FACT DEVICES

A very simple electric network is under consideration in which a transmission line is being fed at one end by a generator G and load is connected at the other end. There are two buses in the system one is at sending end and other is at receiving end of the transmission line. Active power being transmitted is equal to the power produced by the generator as it is assumed lossless.



**Fig.1 Simple Electrical Network**

As we know transmission line equation can be given as

$$P=\frac{V\_{1}V\_{2}}{X}\sin(\left(θ\_{1}-θ\_{2}\right))$$

$$P=Active power$$

$V\_{1}= $Sending end voltage

$V\_{2}$= Receiving end voltage

X= Series line reactance

$θ\_{1}$=Phase angle of sending end voltage

$θ\_{2}$=Phase angle of receiving end voltage

We want to control power flow in AC transmission line because of the following advantages.

* When a transmission system is subjected to disturbances such as line outage, line trip, generator outage or sudden increase in load then we change power flow under these dynamic conditions to ensure system reliability and security with the help of power flow control.
* When we want to enhance power system transmission capacity then we control power flow in AC transmission line.

As the line length increases series line reactance is also increases and power flow in a transmission line is inversely proportional to series line reactances.Power flow decrease as a function of line length. In these situations FACTS controllers incorporate the electrical power system for power flow control.

 Facts Controllers serves the following purposes:

1. Regulation of the power flows in prescribed transmission routes.

2. Secure loading of transmission lines closer to their thermal limits.

3. Prevention of cascading outages of supply by contributing to emergency control.

4. Damping of oscillations that can threaten security of power system or limit the usable line capacity.

The technology needed for this is high power electronics with real time operating control. The realization of such an overall system optimization control should be considered as an additional objective of FACTS controllers.

**Types of FACTS Controllers**

**Shunt Controllers** Shunt controllers inject current into the system at the point of connection. When a variable shunt impedance is connected to the line voltage it causes a variable current flow and hence represents injection of current into the line. As long as the injected current is in phase with the line voltage, the shunt controller only supplies or consumes reactive power. Any other phase relationship between voltage and current will involve handling of real power as well. Shunt controllers include STATCOM, TCR, TSR, TSC, and TCBR.

**Series Controllers** Series controllers inject voltage in series with the line. As long as the voltage is in phase q with the linecurrent, the series controller only supplies or consumes variable reactive power. Any other phaserelationship between voltage and current will involve handling of real power as well. Series controllers include SSSC, IPFC,TCSC, TSSC, TCSR, and TSSR.

**Combined Series-Series Controllers** It is a unified controller in which series controllers provide independent series reactive compensation for each line and also transfer real power among the lines via the proper link. The real power transfercapability of the unified series-series controller, referred to as IPFC, makes it possible to balance both real and reactive power flow in the lines and thereby maximizing the utilization of thetransmission system.

**Combined Series-Shunt controllers** Combined shunt and series controllers inject current into the system with the shunt part of the controller and voltage in series in the line with the series part of the controller. However, when the shunt and series controllers are unified, real power can be exchanged between the series and shunt controllers via the proper link. Combined series-shunt controllers include UPFC, Thyristor controlled phase shifting transformer TCPST, and Thyristor controlled Phase Angle Regulator TCPAR.

**Static synchronous compensator STATCOM.** STATCOM is static var compensator whose capacitive or inductive output current can be controlled independent of the ac system voltage. STATCOM is connected in shunt with the AC system. The injected current by STATCOM is either adjusted to control the bus voltage magnitude or the reactive power injected at the bus.

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**Fig 2.Shunt connected STATCOM**

**Static var compensator SVC.** SVC is a shunt-connected static var generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain the bus voltage. SVC can be considered as a “first generation” FACTS controller and uses thyristor controllers. Static VAR Compensator (SVC) solves dynamic voltage problems by providing high performance fast dynamic voltage control under steady state and dynamic conditions. They have been used for a number of years to improve transmission line economics because of its accuracy, availability and fast response.

The main advantages are:

* SVCs are used to dampen power swings.
* Reduce System losses by optimized reactive power control.

SVCs are used to improve transient stability. Typically an SVC comprises one or more banks fixed or switched shunt capacitor bank or reactors, of which at least one bank is of thyristors.

**Static synchronous series compensator SSSC.** Static Synchronous Series Compensator is connected in series with the AC system. SSSC is a static synchronous generator whose output voltage is in phase with line current for the purpose of controlling the transmitted electric power. The output current is adjusted either to control nodal or bus voltage magnitude or reactive power injected at one of the terminals of series connected transformer. The schematic diagram of typical Static Synchronous in show in Fig 3.

**Fig 3.Series connected SSSC**

**Thyristor controlled reactor TCR.** TCR is a shunt-connected thyristor-controlled inductor whose effective reactance is varied in a continuous manner by partial-conduction control of the thyristor valve.

**Thyristor switched capacitor TSC.**TSC is a shunt-connected thyristor-switched capacitor. Its effective reactance is varied in a stepwise manner by full- or zero-conduction operation of the thyristor valve.

**Thyristor switched reactor TSR.** TSR is a shunt-connected thyristor-switched inductor. Its effective reactance is varied in a stepwise manner by full- or zero-conduction operation of the thyristor valve.

**Thyristor controlled braking resistor TCBR.** TCBR is a shunt-connected thyristor-switched resistor, which is controlled to aid stabilization of a power system or to minimize power acceleration of generating units during disturbances.

**Thyristor Controlled series capacitor TCSC.** TCSC is basically 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.

**Thyristor switched series capacitor** **TSSC.** TSSC is a capacitive reactance compensator consisting of a series capacitor bank shunted by a thyristor-switched reactor to provide a stepwise control of series capacitive reactance.

**Thyristor controlled series reactor TCSR.** TCSR is basically an inductive reactance compensator, which consists of a series reactor shunted by a thyristor-controlled reactor to provide a smoothly variable series inductive reactance.

**Thyristor switched series reactor TSSR.** TSSR is an inductive reactance compensator consisting of a series reactor shunted by a thyristor-controlled reactor to provide a stepwise control of series inductive reactance.



**Fig 4. Schematic Diagram of TCSC&TCSR**

**Thyristor controlled phase shifting transformer TCPST.** TCPST provides rapidly variable phase angle. It is a phase-shifting transformer adjusted by thyristor. This controller is also referred to as TCPAR.

**Unified power flow controller UPFC.**.Unified Power Flow Controller consists of a STATCOM and SSSC connected in such a way that they share a common dc capacitor. SSSC and STATCOM are controlled to provide concurrent real and reactive series line compensation without an external electric energy source. The UPFC proposed is the most versatile FACTS controller for the regulation of voltage and power flow in a transmission line. UPFC is one of the FACTS devices which provide simultaneous control of all basic parameters of power system (transmission voltage, line impedance and phase angle) and precede dynamic compensation of power system. UPFC can fulfill the functions of STATCOM, SSSC and phase shifter. A typical diagram of UPFC is shown in fig 5.

**Fig 5. Schematic Diagram of UPFC**

**Generalized unified power flow controller GUPFC.** GUPFC can effectively control the power system parameters such as bus voltage, and real and reactive power flows in the line. It can control five quantities, i.e., a bus voltage and independent active and reactive power flows in the two lines. The real power is exchanged among shunt and series converters via a common dc link.

**Inter phase power controller IPC.** IPC is a series-connected controller consisting of inductive and capacitive branches in each phase. In IPC mechanical and electronic switches are used to adjust the active and reactive power by controlling phase shifts and/or the branch impedances.

**Thyristor controlled voltage limiter TCVL.** TCVL is a thyristor-switched metal-oxide varistor. It is used to limit the voltage across its terminals during transient conditions.

**Thyristor controlled voltage regulator TCVR.** TCVR is a thyristor-controlled transformer. It can provide variable in-phase voltage with continuous control.

**Interline power flow controller IPFC.** IPFC is a combination of two or more SSSCs that are coupled via a common dc link to facilitate bi-directional flow of real power between the ac terminals of the SSSCs. These are controlled to provide independent reactive compensation for the adjustment of real power flow in each line and maintain the desired distribution of reactive power flow among the lines. If a STATCOM is coupled to the IPFC common dc link it provides shunt reactive compensation and supply or absorb the overall real power deficit of the combined SSSCs. The objective of introducing this controller is to address the problem of number of transmission lines connected at a substation. The schematic diagram of two convertor IPFC is shown in fig 6.



**Fig 6. A two converter IPFC**

In Power system different transients occurs that may disturb the performance of the whole system. FACTS controllers can be used improve the system performance. Following table describes some power system controls and their solution from FACTS controllers.

**Table 1:Control parameters and suggested solution from FACTS devices**

|  |  |
| --- | --- |
| **Desired control Parameters** | **Suggested Solution From FACTS Controllers** |
| Voltage control | SVC,TSR,STATCOM |
| Var Compensation | STATCOM,TCR,TSC |
| Damping Oscillations | STATCOM,SVC,TCVR |
| Voltage stability | SSSC,TCSC,TSSC |
| Trasient and Dynamic Stability | SSSC,TCSC.TSSC |
| Active power control | TCPST,UPFC |
| Reactive power control | IPFC,TCVR |
| Active& Reactive power control | UPFC,GUPFC |
| Fault Current limiting | TCSR,TSSR,UPFC |

V. CONCLUSION

This paper has presented various FACTS controllers and analyzed their control attributes. FACTS controllers are basically power electronics based devices that offer an opportunity to enhance controllability, stability, and power transfer capability of ac transmission systems. There has been considerable progress in the application of FACTS controllers over the past few years. FACTS are host of controllers. System planner can choose particular controller based on cost benefit analysis. Reactive power compensation, voltage control and power flow control are main attributes of FACTS controllers. In deregulated electricity markets, the operation of the transmission system will be closer to its physical limits. The necessity to design electric power networks providing the maximal transmission capacity with minimal costs is a great engineering challenge for which a powerful solution is FACTS controllers. There is every reason to believe that in a decade or so FACTS controllers will revolutionize electrical power transmission systems by making them more reliable, optimally utilized and better controlled.

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