ISSN XXXX XXXX © 2019 IJESC

Research Article Volume 9 Issue No.1

Power System Stability, Efficiency and Controllability Improvement using Facts Devices

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Abstract:
This paper presents a comprehensive review on the research and development in power system stability enhancement using FACTS devices. In past two decades power demand has increased substantially while expansion of power generation has been severely limited due to limited resources and environmental restrictions. Flexible AC transmission System or FACTS have been mainly used for solving various power system problems .FACTS are devices which allow flexible and dynamic control of power system. This paper is aimed towards benefits of using FACTS devices with the purpose of improving the operation of electric power system. It includes stability, controllability improvement of power system operation using FACTS devices.

Keywords: FACTS, SVC, TCSC, TCPS, STATCOM, SSSC, UPFC, IPFC.

I. INTRODUCTION

A flexible AC transmission system refers to system consisting of power electronic devices along with power system devices to enhance the controllability and stability of transmission system and increase power transfer capabilities. FACTS controllers offer opportunity to regulate the transmission of alternating current (AC), increasing or decreasing the power flow in specific lines and responding instantaneously to stability problems.

The potential of this technology is based on the possibility of controlling the route of power flow and ability to connect network that are not adequately interconnected giving the possibility of trading energy between distant agents. Basically the FACTS system is used to provide controllability of hgh voltage side of network by incorporating power electronic devices to introduce inductive or capacitive power in network. Flexible AC transmission systems (FACTS) have gained a great interest during last few years due to recent advancements in power electronics. FACTS devices have been mainly used for solving various power system steady state control problems such as voltage regulation, power flow control, transfer capability enhancement.

As a supplementary function enhancing power system stability using FACTS controllers have been extensively studied and investigated. Generally it is not cost efficient to install FACTS device for sole purpose of power system stability enhancement. In this paper current status of power system stability enhancement, efficiency and controllability using FACTS controllers is discussed and reviewed. This paper is organised as follows;

The overview of FACTS and development in present in section 2. Section 3 discusses potential of first generation of FACTS devices to enhance low frequency stability while potential of second generation of FACTS is discussed in section 4. In section 5 some issues related to installation of FACTS are discussed. In Section 6 the application of FACTS controllers is summarised. In section 7 some benefits of FACTS controllers are reviewed. Some conclusion remarks of paper are highlighted in section 8.

II. FACTS DEVICES

Overview:
In 1980's the electrical power research institute (EPRI) formulated the vision of Flexible AC Transmission System (FACTS) in which various power electronic based controllers regulate power flow and transmission voltage and mitigate dynamic disturbances. Generally the main objective of (FACTS) is to increase usable transmission capacity of linnes and control power flow over designated transmission routes. Hingorani and Gyugyi [1] and Hingorani [2; 4] proposed the concept of FACTS.. Edris *et al.* [5] proposed terms and definitions for different FACTS controllers. There are two generations for realization of power electronics-based FACTS controllers: the first generation and second generation. The first generation employs conventional thyristor-switched capacitors and reactors, and quadrature tap-changing transformers, the second generation employs gate turn-off (GTO) thyristor-switched converters as voltage source converters (VSCs). The first generation has resulted in the Static Var Compensator (SVC), the Thyristor-Controlled Series Capacitor (TCSC), and the Thyristor-Controlled Phase Shifter (TCPS) [6;7]. The second generation has produced the Static Synchronous Compensator (STATCOM), the Static Synchronous Series Compensator (SSSC), the Unified Power Flow Controller (UPFC), and the Interline Power Flow Controller (IPFC) [8–11]. The two groups of FACTS controllers have distinctly different operating and performance characteristics. The thyristor-controlled group employs capacitor and reactor banks with fast solid-state switches in traditional shunt or series circuit arrangements. The thyristor switches control the on and off periods of the fixed capacitor and reactor banks and thereby realize a variable reactive impedance. Except for losses, they cannot exchange real power with the system. The voltage source converter (VSC) type FACTS controller group employs self-commutated DC to AC

converters, using GTO thyristors, which can internally generate capacitive and inductive reactive power for transmission line compensation, without the use of capacitor or reactor banks. The converter with energy storage device can also exchange real power with the system, in addition to the independently controllable reactive power. The VSC can be used uniformly to control transmission line voltage, impedance, and angle by providing reactive shunt compensation, series compensation, and phase shifting, or to control directly the real and reactive power flow in the line [11].

III. FIRST GENERATION OF FACTS

3.1 Static VAR Compensator (SVC)

SVC is an electrical device for providing fast-acting reactive power compensation on high voltage electricity transmission networks. SVCs are part of the FACTS device family, regulating voltage and stabilizing the system the system. It is known that the SVCs with an auxiliary injection of a suitable signal can considerably improve the dynamic stability performance of a power system [12-18]. The term "static" refers to the fact that the SVC has no moving parts (other than circuit breakers and disconnects, which do not move under normal SVC operation). Genetic algorithms and fuzzy logic based approaches have been proposed for SVC control [19–25]. Prior to the invention of the SVC, power factor compensation was the preserve of large rotating machines such as synchronous condensers. The SVC is an automated impedance matching device, designed to bring the system closer to unity power factor. If the power system's reactive load is capacitive (leading), the SVC will use reactors (usually in the form of Thyristor-Controlled Reactors) to consume VARs from the system, lowering the system voltage. Under inductive (lagging) conditions, the capacitor banks are automatically switched in, thus providing a higher system voltage. It is observed that SVC controls can significantly influence nonlinear system behavior especially under high-stress operating conditions and increased SVC gains.

SVC can be used for,

- ●Oscillating Damping
- ●Sub synchronous Resonance (SSR)
- ●Reactive Power Support

3.2 Thyristor Controlled Series Capacitor (TCSC)

TCSC is used in power system to dynamically control the reactance of a transmission line in order to provide sufficient load compensation. The benefits of TCSC are seen in its ability to operate in different modes. These traits are very desirable since loads are constantly changing and cannot be predicted. A thyristor controlled series capacitor is composed of series capacitor which has parallel branch including a thyristor controlled reactor. TCSC is a series controlled capacitive reactance that can provide continuous control of power on AC line over a wide range. The function of TCSC can be comprehended by analyzing the behavior of variable inductor connected in series with fixed capacitor. TCSC operates in different modes depending on when the thyristor for inductive branch are triggered.

The modes of operation are:

● Blocking Mode: Thyristor valve is always off, opening inductive branch and effectively causing TCSC to operate.

●Bypass Mode: Thyristor valve is always on, causing TCSC to operate as capacitor and inductor in parallel reducing current through TCSC.

●Capacitive boost Mode; Forward voltage thyristor valve is triggered slightly before capacitor voltage crosses zero to allow current to flow through inductive branch adding to capacitive current.

3.3 Thyristor controlled phase shifter (TCPS)

The TCPS is one of the potential options of recently proposed FACTS devices. Researchers have developed different TCPS schemes in the literature [26-33]. Ise *et al*. [26] compared between two different TCPS schemes. Compared with other FACTS devices, little attention have been paid to TCPS modeling and control. The TCPS control problem has been investigated using linear control techniques [26-27]. Jiang *et al.* [34] proposed a TCPS control technique based on nonlinear variable structure control theory. In their control scheme the phase shift angle is determined as a nonlinear function of rotor angle and speed. However, in real-life power system with a large number of generators, the rotor angle of a single generator measured with respect to the system reference will not be very meaningful. Tan and Wang [35] proposed a direct feedback linearization technique to linearize and decouple the power system model to design the excitation and TCPS controllers.

IV. SECOND GENERATION OF FACTS

4.1 Static Compensator (STATCOM)

A STATCOM is a regulating device used on alternating current electricity transmission networks. It is based on a power electronics voltage-source converter and can act as either a source or sink of reactive AC power to an electricity network. If connected to a source of power it can also provide active AC power. Application of STATCOM for stability improvement has been discussed in the literature [36-46]. The effectiveness of the STATCOM to control the power system voltage was presented in [37]. Usually a STATCOM is installed to support electricity networks that have a poor power factor and often poor voltage regulation. There are however, other uses, the most common use is for voltage stability. From the power system dynamic stability viewpoint, the STATCOM provides better damping characteristics than the SVC as it is able to transiently exchange active power with the system. Every equipment has some limitations so STATCOM also have some limitations of supplying or absorbing reactive power. The limitations in STATCOM is imposed by current carrying capacity of force commutated device like GTO. Therefore if the operation of STATCOM reaches its limitation it does not further increase or decrease its output voltage rather it supplies or absorbs fixed reactive power equal to its limiting value at a fixed voltage and current and acts like constant current source. This mode of operation of STATCOM is called as VAR control mode.

4.2 Static Synchronous Series Compensator (SSSC)

The SSSC has been applied to different power system studies to improve the system performance [47–53]. There has been some work done to utilize the characteristics of the SSSC to enhance power system stability [54; 55]. Static Synchronous Series Compensator (SSSC) device work the same way as the STATCOM. It has a voltage source converter serially connected to a transmission line through a transformer. SSSC is able to exchange active and reactive power with the transmission system. But if our only aim is to balance the reactive power, the energy source could be quite small. The injected voltage can be controlled in phase and magnitude if we have an energy source that is big enough for the purpose.

With reactive power compensation only the voltage is controllable, because the voltage vector forms 90º degrees with the line intensity.

4.3 Unified Power Flow Controller (UPFC)

The universal and most flexible FACTS device is the Unified Power Flow Controller (UPFC). UPFC is the combination of three compensators' characteristic; i.e. impedance, voltage magnitude and phase angle, that are able to produce a more complete compensation. A 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 [56]. The three control parameters, *i.e.* the bus voltage, transmission line reactance, and phase angle between two buses can be controlled either simultaneously or independently. A UPFC performs this through the control of the in-phase voltage, quadrature voltage, and shunt compensation. The UPFC is the most versatile and complex power electronic equipment that has emerged for the control and optimization of power flow in electrical power transmission systems. The UPFC was devised for the real-time control and dynamic compensation of ac transmission systems, providing multifunctional flexibility required to solve many of the problems facing the power industry. Within the framework of traditional power transmission concepts, the UPFC is able to control, simultaneously or selectively, all the parameters affecting power flow in the transmission line. Alternatively, it can independently control both the real and reactive power flow in the line unlike all other controllers. A current injected UPFC model for improving power system dynamic performance was developed by Meng and So [57].

4.4 Interline Power Flow Controller (IPFC)

The latest generation of FACTS devices, namely the IPFC, is the combination of multiple series compensators, which are very effective in controlling power flows in transmission lines. IPFC and the generalized unified power flow controller are two innovative configurations of the convertible static compensator of FACTS. Gyugyi et al [58] presented an IPFC which is a new concept for the compensation and effective power flow management of multi-line transmission systems. Parimi et al [59] investigated the use ofthe IPFC based controller in damping of low frequency oscillations. IPFC has different applications equating active and reactive power flow through compensated transmission lines, transmitting power from over loaded lines to other lines, compensation of resistive voltage drops through lines and improving the performance of compensated system when dynamic disturbances occur are some applications of IPFC [60].In general IPFC consists of N (the number of compensated lines by IPFC) voltage source inverters which have common dc link. In other words it can be said that IPFC consists of number of SSSC with common dc link. [60].

V. FACTS INSTALLATION ISSUES

For the maximum effectiveness of the controllers, the selection of installing locations and feedback signals of FACTS-based stabilizers must be investigated. On the other hand, the robustness of the stabilizers to the variations of power system operation conditions is equally important factor.

5.1 Location and Feedback Signals

Generally, the location of FACTS devices depends on the objective of the installation. The optimal location can be governed by increasing system loadability [61–63], minimizing the total generation cost [64], and enhancing voltage stability [65]. Wang *et al.* [66] presented two indices for selecting the optimal location of PSSs or FACTS-based stabilizers. The first index was based on the residue method while the second index was based on damping torque analysis. This work has been further developed in [67] where a new method independent of the Eigen solution to identify the optimal locations and feedback signals of FACTS-based stabilizers was proposed. The new method avoids difficulty of Eigen solution and reduces the computation cost.

5.2 Coordination among Different Control Schemes

Mahran *et al.* [68] presented a coordinated PSS and SVC controller for a synchronous generator. However, the proposed approach uses recursive least squares identification which reduces its effectiveness for on-line applications. Various approaches for coordinated design of PSS and SVC are also presented in [69–71]. Abido and Abdel-Magid [72–74] presented coordinated design of control schemes for the excitation and different FACTS controllers. The coordination of multiple FACTS controllers in the same system as well as in the adjacent systems must be investigated extensively and implemented to ensure the security of power-system operation.

5.3 Performance Comparison

The relative efficacy of different FACTS controllers in enhancing of power system stability is investigated [75–79]. The capabilities of PSS, SVC-based stabilizer, TCSC-based stabilizer, and TCPS-based stabilizer to control the electromechanical mode over wide range of operating conditions were discussed in [80]. The UPFC is by far the best controller, as it provides independent control over the bus voltage and the line real and reactive power flows.

5.4 Application of FACTS

FACTS controllers can be used for various applications to enhance power system performance. One of the greatest advantages of using FACTS controllers is that it can be used in all the three states of the power system, namely:
(1) Steady state,
(2) Transient and
(3) Post transient steady state.

5.5 STEDY STATE APPLICATION

Various steady state applications of FACTS controllers include voltage control (low and high), increase of thermal loading, post-contingency voltage control, loop flows control, reduction in short circuit level and power flow control. SVC and STATCOM can be used for voltage control while TCSC is more suited for loop flow control and for power flow control.

5.6 DYNAMIC APPLICATION

Dynamic application of FACTS controllers includes transient stability improvement, oscillation damping (dynamic stability) and voltage stability enhancement.
One of the most important capabilities expected of FACTS applications is to be able to reduce the impact of the primary disturbance. The impact reduction for contingencies can be

achieved through dynamic voltage support (STATCOM), dynamic flow control (TCSC) or both with the use of UPFC.

5.7 TRANSIENT STABILITY ENHANCMENT

Transient instability is caused by large disturbances such as tripping of a major transmission line or a generator and the problem can be seen from the first swing of the angle. FACTS devices can resolve the problem by providing fast and rapid response during the first swing to control voltage and power flow in the system.

5.8 DYNAMIC VOLTAGE CONTROL

Shunt FACTS controllers like SVC and STATCOM as well as UPFC can be utilized for dynamic control of voltage during system contingency and save the system from voltage collapse and blackout.

5.9 Application In Deregulated Environment

Apart from its traditional application for voltage control, power flow control and enhancing steady state and dynamic limits, FACTS controllers are finding new applications in the present deregulated environment. One of the applications is in controlling the "parallel flow" or "loop flow". Loop flow results in involuntary reduction in transmission capacity that may belong to some other utility and hence foreclose beneficial transactions through that line. FACTS devices can also be implemented to ensure the economy in operation by placing it in a suitable line such that least cost generators can be dispatched more. It can also be used to reduce the losses in the system. Yet, another application is to use FACTS to relieve the congestion in the system. FACTS devices can be strategically placed such that congestion cost is reduced, curtailment is decreased and price volatility due to congestion is minimized.

VI. BENEFITS

The benefits of utilizing FACTS devices in electrical transmission systems can be summarized as follows:

- Increasing the loadability of the system
- Power quality improvement
- Increase power transfer capability of a line
- Mitigate sub-synchronous resonance (SSR)
- Improve system transient stability limit
- Alleviate voltage stability
- Load compensation
- Limit short circuit currents
- Enhance system damping

VII. CONCLUSION

In this review, current status of power system stability enhancement using FACTS controllers is discussed. The overview of FACTS and different types of FACTS controllers and their ability to enhance system stability is also addressed. FACTS installation issues, location and feedback signal used for design of FACTS controllers is discussed. The coordination problem among different control schemes is considered. Performance comparison of different FACTS controllers is reviewed. A brief review of FACTS applications is also present.

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