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A Review on Application of FACTS Devices in Power System Stability Improvement

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***Abstract*—**The increase in demand of power has increased the complexity in power systems. This complexity often makes it difficult to obtain a good understanding of the behaviour of a system. The power generation and transmission are affected due to limited resources, environmental restrictions and other losses. The flexible alternating current transmission system (FACTS), an advanced technology based on power electronics, provides an opportunity to improve controllability, stability, and power transfer capability of AC transmission systems. This article presents a comprehensive review and evaluation of FACTS controllers in comparison with conventional power system stabilizers. Several technical publications related to FACTS installations have been highlighted and performance comparison of different FACTS controllers has been discussed.

***Keywords*—** SMIB system; small signal stability; low frequency oscillations (LFO); static synchronous compensator; unified power flow controller; STATCOM and TCSC.

I. Introduction

Power system stability has been recognized as an important problem for secured system operation since the 1920s. It has been reported that many major blackouts in the world like in Japan, a large-scale power failure that occurred in the Tokyo metropolitan area in 1987 (about an 8-GW loss) and part of the problems that led to the North American blackout of August 2003 have been the direct outcomes of power system instability[1], [2]. In the last two decades, power systems have been operated under much more stressed conditions than they usually had in the past. The factors responsible for this include continuing growth in interconnections, the use of new technologies, bulk power transmissions over long transmission lines, environmental pressures on transmission expansion, increased electricity consumption in heavy load areas (where it is not feasible or economical to install new generating plants), new system loading patterns due to the opening up of the electricity market, growing use of induction machines and large penetration of wind generators and local uncoordinated controls in systems. Thus, power system stability defined as the ability of the system to bring back its operation to steady state condition within minimum possible time after having undergone some sort disturbance in the line is of utmost importance [3].

Today, large interconnected power systems are operating upto their stability limits for reliable and economical operation. However, low frequency oscillations (LFO) with the frequencies in the range of 0.1 to 2 Hz are one of the direct results of perturbations in the interconnected grid systems. If LFO are not damped they make the interconnected system vulnerable to the risk of instability. These oscillations would limit the total and available transfer capability (TTC and ATC) of the transmission line by requiring higher safety margins [4]. Thus, in order to maintain the stability of the entire system, it is urgent to damp the electromechanical oscillations as soon as possible.

II. SMIB System

All the machines in the power exporting area in a power system can be reduced to an equivalent generator and all the machines connected to power importing area can be reduced to equivalent synchronous motor. Thus a multimachine system can be converted to a two machine system for ease of analysis. The two machine system can be further reduced to one synchronous machine connected to infinite bus system-a constant voltage constant frequency system also known as Single Machine Infinite Bus (SMIB) system. The SMIB system is as shown in figure 1.

Fig.1. Single machine infinite bus system.

The block diagram of linearized model of Single Machine Infinite bus system to analyze the various stability phenomena is as shown in the block diagram in figure 2. The constants of the model depend on the system parameters and the operating conditions [5]. The various stability phenomena can be understood by considering the basic SMIB system.

Power system stability is primarily classified as rotor angle stability, voltage stability and frequency stability. Rotor angle stability is further divided into small signal stability, dynamic and transient stability.

A. *Small Signal Stability*

Small signal stability means the ability of synchronous machines of an interconnected power system to remain in synchronism after being subjected to a disturbance. The rotor angle stability problem involves the study of the electromechanical oscillations inherent in power systems.

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Small signal instability is due to insufficient damping torque leading to low frequency electromechanical oscillations in system. The stability of the system during such oscillatory period can be quantified in terms of the damping ratio of the system. If the damping ratio is negative, the system becomes oscillatory unstable. While if the damping ratio is positive, the system becomes stable after few oscillations.

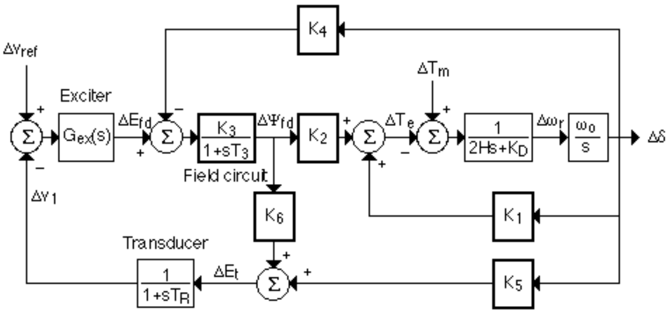

Fig. 2. Block Diagram of SMIB system.

B. *Dynamic Stability*

The power system is said to be dynamically stable if the oscillations do not acquire high amplitude and die out quickly. The dynamic stability is concerned with the small disturbances lasting for longer time. Dynamic stability also refers to slower events, for instance, power oscillations occurring from disconnection of large amounts of generation or load, or switching of some lines.It has been used to denote different phenomena by different authors. In the North American literature, it has been used mostly to denote small-disturbance stability in the presence of automatic controls (particularly, the generation excitation controls) as distinct from the classical "steady-state stability" with no generator controls. In the European literature, it has been used to denote transient stability.

C. *Transient Stability*

The ability of a synchronous power system to return to stable condition and maintain its synchronism following a relatively large disturbance arising from general situations like switching 'on' and 'off' of circuit elements, or clearing of faults etc. is referred to as the transient stability in power system. More often than not, the power generation systems are subjected to faults of this kind, and hence it is extremely important for power engineers to be wellversed with the stability conditions of the system. In general practice studies related to transient stability in power system are done **o**ver a very small period of time equal to the time required for one swing, which approximates to around 1 sec or even less. If the system is found to be stable during this first swing, it is assumed that the disturbance will reduce in the subsequent swings, and the system will be stable thereafter as is generally the case.

D. *Voltage Stabilty*

"Voltage stability is the ability of a power system to maintain steady acceptable voltages at all buses in the system under normal operating conditions and after being subjected to a disturbance" [6]. Voltage stability problems occur more frequently in a heavily loaded system. The change in voltage is directly proportional to change in load and hence voltage stability is sometimes termed as load stability. The reactive power compensation close to the load centres as well as at critical buses in the network is essential for overcoming voltage instability.

E. *Frequency Stability*

Frequency stability refers to the ability of a power system to maintain steady frequency following a severe system upset resulting in a significant imbalance between generation and load. Instability that may result leads to tripping of generating units and/or loads. Power System time scales show the stability as a function of time as per figure 3.

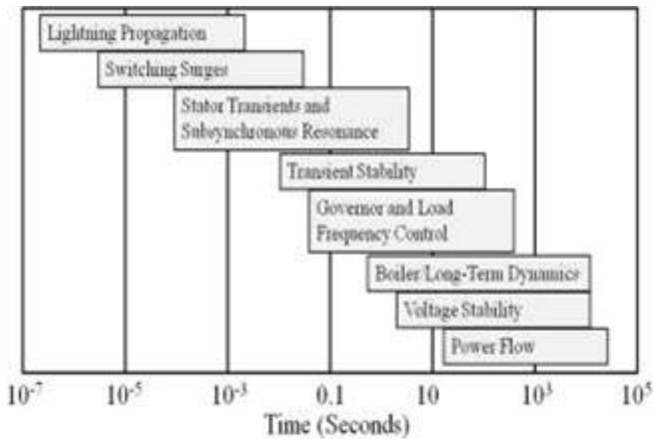

Fig. 3. Power system time scales.

III. POWER SYSTEM STABILIZER

Power System Stabilizers are supplementary control devices which are installed in generator excitation systems. Their main function is to improve stability by adding an additional stabilizing signal to compensate for undamped oscillations [7].

The conventional PSS was first suggested in the 1960s and classical control theory, defined in transfer functions, was employed for its design. Later the revolutionary work of DeMello and Concordia [8] in 1969, control engineers, as well as power system engineers, have made significant assistance in PSS design and applications for both single and multi-machine power systems. Basler, Schaefer et al. [9] presented the concept of small signal stability in view of power generating plants as equipped with continuously acting automatic voltage regulators. A light was thrown on evolution of power oscillations of small magnitude and low frequency with the growth of power transfer. In some cases, this presented a limitation on the amount of power to be transmitted within the system. This paper presented the role of power system stabilizers employed commonly for the purpose of improving the small signal stability of the power system.

A generic PSS block diagram is shown in figure 4. It consists of three blocks: a gain block, a washout block and a phase compensation block. An additional filter may be needed in the presence of torsional modes. Depending on the

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availability of input signals, PSS can use single or multiple inputs [7-10].

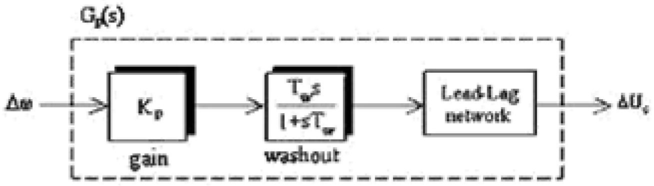

Fig. 4. Power system stabilizer.

Nowadays, the conventional lead-lag power system stabilizer is widely used by the power system utility]. Other types of PSS such as proportional-integral power system stabilizer (PIPSS) and proportional-integral-derivative power system stabilizer (PID-PSS) have also been proposed. The performance of PSS gets affected by network configurations, load variations etc., hence the installation of FACTS devices (based on power semiconductor technology has been suggested by researchers to achieve appreciable damping of system oscillations.

IV. Flexible AC Transmission Systems (FACTS)

The FACTS initiative was originally launched in 1980's to solve the emerging problems faced due to restrictions on transmission line construction, and to facilitate growing power export / import and wheeling transactions among utilities. The basic objectives behind the development of FACTS are

- to increase power transfer capability of transmission systems and to keep power flow over designated routes
- significantly increase the utilization of existing (and new) transmission assets,
- play a major role in facilitating contractual power flow in electricity markets with minimal requirements for new transmission lines.

The Flexible AC transmission systems (FACTS) [11] devices have revolutionized the electrical power transfer. With the advent of thyristor technology, the dream of power transmission up to maximum stability limit has turned into reality. This has initiated a new and more versatile approach to control the power system in a desired way. FACTS are devices which allow the flexible and dynamic control of power systems.

A. Static Synchronous Series Compensator (SSSC)

The static synchronous series compensator (SSSC) is one of the series FACTS devices based on a solid-state voltage source converter (VSC) which generates a controllable ac voltage in quadrature with the line current [13]. By this way, the SSSC appears as an inductive or capacitive reactance and hence controls the power flow in the transmission lines as shown in fig 5. In [14], authors have developed the damping function for the SSSC. SSSC damping controller can be designed using various methods, for example, in [14] authors have used the phase compensation method. The main problem associated with these methods is that the control process is based on the linearized machine model. The other mostly used method is the proportional-integral (PI) controller. Even though the PI controllers offer simplicity and ease of design, its performance deteriorate when the system conditions vary widely or large disturbances occur [15], [16].

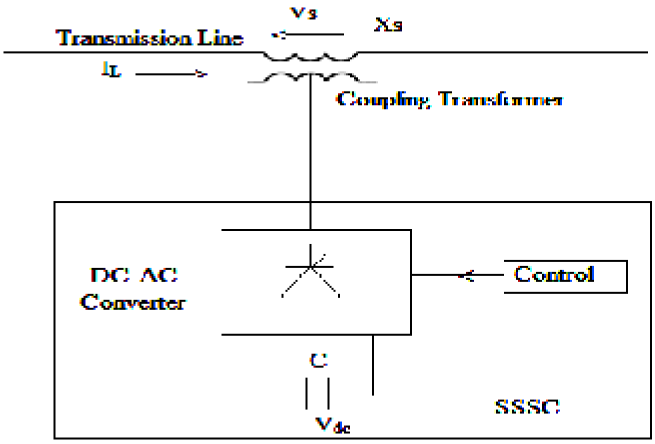

Fig. 5. Static series synchronous compensator.

B. Static Synchronous Compensator (STATCOM)

The fundamental principle of a STATCOM installed in a power system is the generation of ac voltage by a voltage source inverter (VSI) connected to a dc capacitor. The active and reactive power transfer between the power system and the STATCOM is caused by the voltage difference across the reactance. The STATCOM can increase transmission capacity, damp low frequency oscillation, and improve transient stability. The STATCOM is represented by a voltage source, which is connected to the system through a coupling transformer as shown in the figure 6. Mathematical modeling and analysis of static compensator (STATCOM) is presented in [18], [19]. It explains the use of STATCOM for improvement of transient stability and power transfer. It also explains the modes of operation of STATCOM in voltage control mode and static VAR control mode.

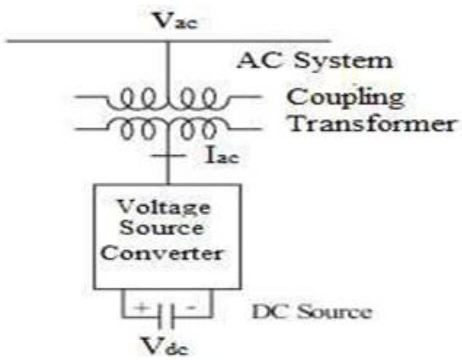

Fig. 6. Static synchronous compensator.

C. Thyristor-Controlled Series Compensation (TCSC)

Thyristor-Controlled Series Compensation (TCSC) is used in power systems 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 control the amount of compensation of a transmission line,

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and in its ability to operate in different modes. The basic structure of a TCSC can be seen in fig.7:

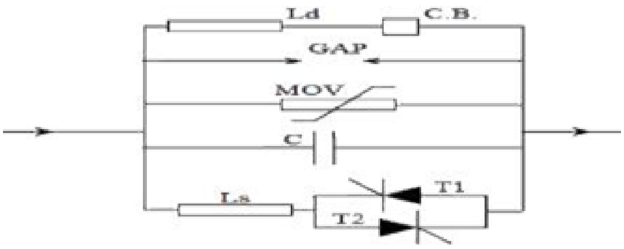

Fig.7 Thyristor-controlled series compensator.

D. Unified Power Flow Controller (UPFC)

Unified Power Flow Controller (UPFC) is the most versatile one that can be used to enhance steady state stability, dynamic stability and transient stability. The basic configuration of a UPFC is shown in figure 8. It is considered as the combination of SSSC and STATCOM connected via a DC link capacitor. Hence, UPFC is capable of both supplying and absorbing real and reactive power and it consists of two ac/dc converters. The power balance between the series and shunt converters is a prerequisite to maintain a constant voltage across the dc capacitor. The series branch of the UPFC injects a voltage of variable magnitude and phase angle, so it can exchange real power with the transmission line and improve the power flow capability and transient stability of the line. The shunt converter exchanges a current of controllable magnitude and power factor angle with the power system. The paper presented by Niaki, Iravani, in 1996 [19] provided comprehensive development procedures and final forms of mathematical models i.e., steady state model, small signal(linearized) dynamic model, and state space, large signal model of Unified Power Flow Controller (UPFC) for steady state, transient stability and eigen value studies.

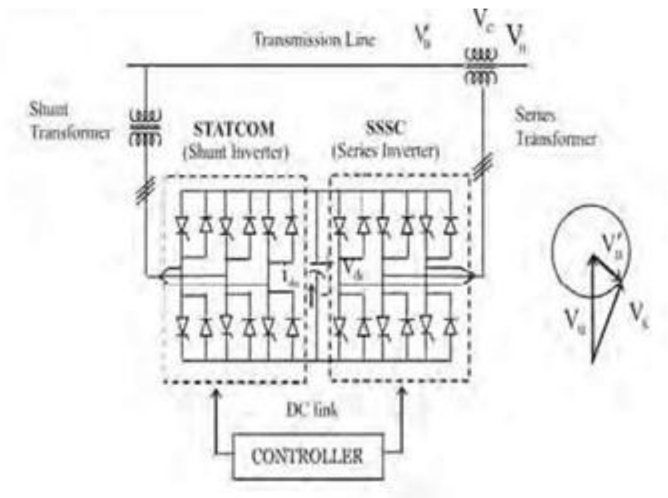

Fig. 8. Basic configuration of UPFC.

The developed formulation was general and independent of PWM scheme used for the switching converters of the UPFC as long as the fundamental frequency components of current and voltage are concerned. The work of Wang in 2000 [20], Z Huaang and Gyugi resulted in the establishment of linearized model of single machine and multimachine power systems installed with UPFC, the application of the Phillips Hefferon Model in the study of the effects of UPFC DC voltage regulator on power system oscillation stability and selection of most effective damping signals for the design of the UPFC damping controller. Tambey, Kothari et al. presented the systematic approach for designing UPFC based damping controllers for damping low frequency oscillations in a power system [21]. mE, mB, δE, δB are the modulation ratio and phase angle of the control signal of each voltage source respectively, and are the input control signals to the UPFC i.e., variation in the control signal result in the creation of damping signal that improve the performance of UPFC. The performance of the four alternative damping controllers i.e., (mE, mB, δE, δB) was examined considering wide variations in the loading conditions and line reactance (Xe) [18]. The relationship between fundamental component of the converter ac output voltage and voltage across dc capacitor is given as

$$V_{out}=KV_{dc}$$

Where k is coefficient which depends upon on the converter configuration, number of switching pulses and the converter controls.

Low frequency oscillations have been observed in many of the power systems around the world during the past years and some of these are tabulated in table I along with the immediate remedial measures:

V. SUMMARY

Due to small changes in the system, the operating point is always changing. However, there are some operating conditions, which cause the system to go in oscillatory instability mode due to these small changes.

TABLE I. LFOS in power systems.

Case	**Year**	**Frequency of oscillations**	**Remedial Measures**
Southern China Interconnected Power System [23]	2005	0.53, 0.4	PSS tuning of generators selected by participation factor ,HVDC power oscillations damping mode
WR-ER India	2006	0.45	TCSC installed on tie line connecting Eastern and Western Grid
Columbian Power System[22]	2008	0.06	Correcting the models of generators and exciters, Change in governor control parameters.
Continental Europe power system [24]	2011	0.25	PSS tuning of generators in Italy

Low frequency oscillations have been observed in many of

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the power systems around the world during the past years as an example of such instability and some of these are tabulated in TABLE I along with the immediate remedial measures. The various applications of FACTS controllers/devices in restructured power systems are meant to improve the system stability and enhance the power system performance. One of the greatest advantages of utilizing FACTS controllers in power system is that the FACTS controller can be used in three states of the power system i.e., steady state, transient and post transient steady state. However, the conventional devices find little application during system transient or contingency conditions.

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