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Coordinated Control of Power System Stabilizer and FACTS Devices for Dynamic Performance Enhancement – State of Art

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***Abstract*—There are two types of oscillation damping controller in power system which are power system stabilizer (PSS) and flexible ac transmission systems (FACTS). Numerous works have been carried out on the damping of power system low frequency oscillations. This paper addresses an extensive literature review on coordination problem in single-machine and multi-machine power system. It also reviews various types of FACTS controllers. Various methods are proposed in order to enhance the dynamic performance of a power system for coordinated control between FACTS and PSS controller in power system models.**

***Keywords*—PSS; FACTS devices; power system stability.**

I. INTRODUCTION

The changes in the operating condition of an electric power system usually accompany with spontaneous low-frequency oscillations (LFO) [1]. It is inevitable that characteristics of power systems greatly affect the transmission line transfer capability and power system stability. These oscillations can be observed in most power system variables like bus voltage, line current, generator speed and power [2, 3]. Low frequency electromechanical oscillations can be classified into four main categories including local oscillations, interplant oscillations, inters area oscillations and global oscillations. Local or plant modes of oscillations have natural frequencies of about 1 to 2 Hz [4]. Inter area modes of oscillation have lower natural frequencies in the range of 0.1 to 0.7 Hz. In small systems, inter-area oscillations generally have higher natural frequencies than those of large systems. The total number of modes of synchronizing oscillations is equal to one less than the number of interconnected generators [5]. Damping of oscillations is not only important in increasing the transmission capability but also in stabilizing power system conditions following critical faults [6]. The sustained LFO of a power system is due to the lack of damping of the system mechanical mode, and the desired additional damping can be provided by supplementary excitation control. Generally, the damping control methods of power system oscillations can be divided into two following major groups: 1) damping control at generation locations and 2) damping control in the transmission path [7]. PSS and FACTS controllers are acceptable solutions for voltage and oscillatory instability problems, since these controllers increase loading margins and provide additional system damping [8, 9]. The papers published in the field of PSS and FACTS devices can be classified as: (a) mathematical modeling and simulation, (b) optimal placement and feedback signals, (c) characteristics comparison, (d) controller design, (e) power system performance improving and (f) coordination between the PSS and the FACTS. In general, from control point of view, FACTS controllers can be divided into four categories: 1) series controllers, 2) shunt controllers, 3) combined series-shunt controllers and 4) combined series-series controllers [10]. In power system, the main forms of stabilizers are the PSS and FACTS devices. Using only conventional PSS in multi-machine power system may not provide sufficient damping for inter-area oscillations. In power system stability improvement, the coordinated control between PSS and FACTS devices is an important problem.

This paper presents a comprehensive review on the topologies, configurations, and control techniques of coordination PSS and FACTS devices in power system in order to improve different operating parameters such as damping low frequency oscillations, enhancing power system stability, improving the steady-state, and others parameters. Over 70 papers are reviewed and classified broadly into three categories. The first category is based on mechanical switches FACTS devices and PSS. The second category comprises of FACTS devices based on voltage source converter and PSS. The third category is on the hybrid FACTS devices.

II. POWER SYSTEM STABILIZER

Power system stabilizer (PSS) is widely used in power systems in order to contribute to the damping low frequency oscillations. The PSS adds a stabilizing signal to AVR that modulates the generator excitation. A practical PSS must be robust over a wide range of operating conditions and capable of damping the oscillation modes in power system [11]. PSS has been accepted by the utility houses as a viable measure to enhance power system damping to low frequency oscillations in the range of 0.1–3.0 Hz. A PSS model is viewed as an additional control block to enhance system stability. A PSS contains three blocks [12]: 1) the rest block, 2) the washout filter and 3) the phase-compensation. Some commonly used input signals are rotor speed deviation, accelerating power, and frequency deviation [13]. A common structure for PSS is

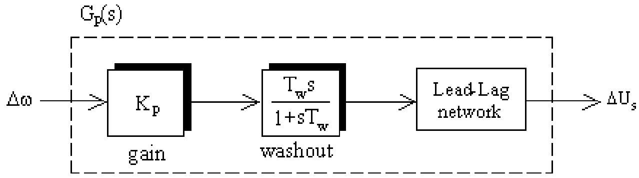

Fig. 1. Conventional power system stabilizer

shown in Fig. 1. A design method for fixed parameter decentralized PSS based on the conventional design technique for interconnected multi-machine power systems has been proposed in [14]. A space recursive least square (SPARLS) algorithm developed for tuning PSS parameters on SMIB power system based PID is proposed in [15] to meet the vulnerable conditions. In [16], the way in which mechanical power variations has been shown in order to influence control performance of PSS loops in DFIG; where PSS signal is applied at the output of the basic controller, the PSS performance characteristics displayed are deemed typical for DFIG control schemes in general.

III. FACTS DEVICES

Development of FACTS devices in power transmission system have led to many applications of these controllers. They are not only improving various stability issues but also providing operating flexibility to power systems [17, 18]. In general, from control point of view, FACTS controllers can be divided into following six categories: 1) TCSC and SSSC, 2) shunt controllers (such as SVC), 3) STATCOM and 4) STATCOM with energy-storage system, 5) combined series-shunt controllers such as UPFC and TCPS, and 6) combined series-series controllers such as IPFC. Generally, FACTS devices can be divided into two major groups: 1) one-port (shunt controller and series controller) and 2) two-port (series-series controller and series-shunt controllers). There are various types of FACTS devices [19]. A current injection model of FACTS controllers is adopted to study dynamic stability of power system which can be easily applied to the linear and the nonlinear analysis, and adopted any kind of voltage source inverter (VSI) type FACTS controllers regardless of model types, as proposed in [20]. A coordination approach for the controller design of multiple HVDC and FACTS wide-area such as SVC and TCSC controls has been presented in [21] and has the aim of stabilizing multiple inter-area oscillation modes in 16-machine 5-area power systems.

IV. COORDINATE CONTROL

A conventional PSS can improve the steady-state stability margin and increase the system positive damping, but it has some drawbacks, such as time consuming tuning and non-optimal damping in the entire operating process [22, 23]. Uncoordinated FACTS-based stabilizers and PSSs always cause destabilizing interactions [24]. A method based on conic programming to shift under-damped or unstable modes into a region of sufficient damping of the complex plane, to design coordinated FACTS and PSS controllers for stabilizing power system oscillations, has been presented in [25]. In [26], a linear programming algorithm has been used for simultaneous coordination of PSS and FACTS device stabilizers in a multi-machine power system for enhancing dynamic performance of the rotor modes of oscillations. A constrained optimization approach for designing coordinated controllers of PSS and FACTS devices has been developed in [27] in order to achieve and enhance small-disturbance stability in multi-machine power systems, where the eigenvalue-eigenvector equations associated with the selected modes form a set of equality constraints in the optimization.

A. Mechanical switches and PSS

Devices in one category essentially replace mechanical switches with power electronics switches. The variable impedance type controllers include: 1) TCSC (series connected), 2) SVC (shunt connected) and 3) TCPS (combined shunt and series). The SVC is connected in shunt with the transmission line for reactive power support and the TCSC is connected in series with the transmission line to transfer more power on the transmission line [28].

a) SVC and PSS: An SVC is a fast controllable to generate or absorb reactive power. If the injected current is in phase quadrature with the line voltage, the controller adjusts reactive power while if the current is not in phase quadrature, the controller adjusts real power [29]. Fig. 2 shows the schematic diagram of a SVC. The SVC is usually composed of two main parts, namely TSC and TCR. In [30] the PSS and SVC have the same controller to improve the power system stability in the SMIB power system, itmens that their coefficients have been optimized by PSO, Chaos and shuffled frog leaping (SFL) algorithms. Coordination of SVC and PSS using generator speed deviation or modal speeds as stabilizing signals to damp the system oscillations has been given in [31], in which the efficacy of controllers for damping SSR under steady-state and faulted conditions has been discussed. A lead-lag structure as a main damping controller for a static SVC has been proposed to diminish power system oscillations [32], where the coordinated design problem of these devices was formulated as an optimization problem to reduce power system oscillations.

b) TCSC and PSS: TCSC is a typical series FACTS device based on the concept of impedance control of the transmission line. It is much more effective than the shunt FACTS devices in the application of power flow control and power system oscillation damping control.

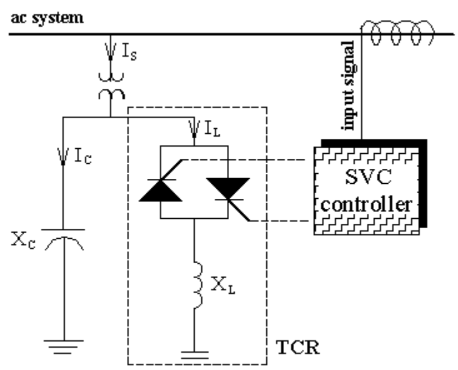

Fig. 2. A SVC installed in a power system

The control device is the thyristor semiconductor switch. A typical TCSC model as shown in Fig. 3 consists of a fixed series capacitor (FC) in parallel with a TCR [33, 34]. An approach based on the use of mixing conventional technology and FACTS technology in a series capacitive compensation scheme has been introduced in [35], which has the potential of enhancing power system dynamics. It has been presented in [36] that an interval type-2 fuzzy controller-based TCSC controllers along with PSS in the system damp out the speed and power oscillations following different critical faults satisfactorily. A combination of TCSC and PSS for enhancing the stability of multi-machine system has been presented in [37], in which the parameters of these controllers are optimized by VURPSO algorithm and GA.

c) TCPS and PSS: A TCPS is a device that injects a variable series quadrature voltage to affect the power flow in a transmission line by modifying both the magnitude and the phase angle. The output voltage phase can be varied relative to that of the input voltage by simply varying the magnitude of the series quadrature voltage [38]. Fig. 4 shows the schematic diagram of a TCPS. A nonlinear coordinated generator excitation and TCPS controller proposed in [39] enhance the transient stability of a power system in which the proposed controller is able to control namely excitation voltage, phase angle and reactance in a coordinated manner. Dynamic performances considering conventional phase lead-lag power system stabilizer and TCPS equipped with conventional lead-controller have been compared in [40]. The study and design of a controller is capable to damp less economical control coordination between PSS and TCPS [41], where genetic algorithm (GA) is utilized to search for optimum controller parameter settings and an optimal pole shifting for multi-input multi-output systems.

B. Voltage source converter and PSS

In general, voltage source converter (VSC) of the FACTS controllers can be divided into (SSSC) (series connected), STATCOM (shunt connected) and UPFC (combined shunt-series) and IPFC (combined series-series). The STATCOM control transmission voltage by reactive shunt compensation, SSSC control the effective transmission impedance, UPFC control all three effective transmission parameters and IPFC is a highly versatile device for fast power flow control [42].

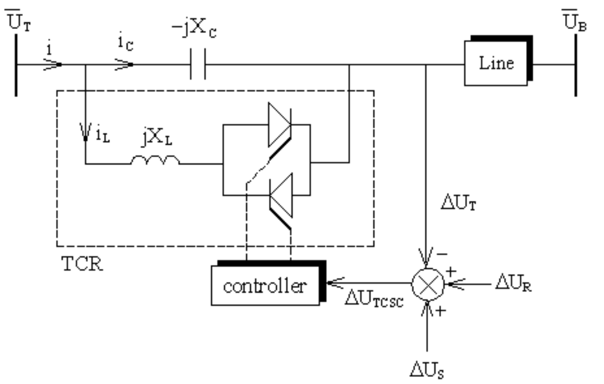

Fig. 3. A TCSC installed in a single-machine infinite-bus (SMIB) power system

a) STATCOM and PSS: An STATCOM is capable of injecting independently controllable reactive power into the system [43]. It provide continuously variable reactive power at its point of connection with the grid [44]. STATCOM uses VSCs with capacitors connected on dc side. The configuration of a STATCOM connected to bus M of a transmission line has been shown in Fig. 5. Two control signals are M (modulation ratio defined by PWM) and ϕ (phase angle defined by PWM). The dc capacitor (C_{DC}) has the function of establishing an energy balance between the input and output during the dynamic change of the var output. The reference signal Q_{REF} and P_{REF} can control the amplitude and phase angle of output voltage, respectively [45]. In general, an STATCOM system can be divided into three key parts: 1) the converter power stage, 2 the passive components and 3) the control system [46]. A minima disturbance attenuation method based on the maximization of the external disturbances of the single machine infinite bus system with STATCOM is considered in [47] based on the back-stepping method. Stabilization of generator oscillations using PID-STATCOM damping controller and PID-PSS has been presented in [48], where the parameters of the proposed damping controllers were solved by left shifting both modes to the desired locations on the complex plane using a unified approach based on modal control theory. The optimal location of an STATCOM and its coordinated design with PSS for power system stability improvement using PSO algorithm have been presented in [49].

b) UPFC and PSS: UPFC has great flexibility to adjust all control parameters: transmission line reactance, bus voltages and phase angle between two buses, either simultaneously or selectively [50]. UPFC consists of two of series and shunt switching converters operated from a common dc bus, as shown in Fig. 6 [51]. The working range of the UPFC angle is between -180° and +180°. The shunt branch of the UPFC consists of another VSC for providing the necessary voltage support to the connected bus and exchanges real power from the bus with the series-connected voltage source [52]. The PSO based output feedback controllers for coordinated designing of the UPFC and the PSS in SMIB power system has been presented in [53], which has an excellent capability in damping power system oscillations and enhancing greatly the dynamic stability of the power system. A control scheme has been introduced in [54] in order to design an advanced PSS, and analyze it comprehensively, in which the result has been given for the dynamic control of power transmission and damping oscillations with UPFC.

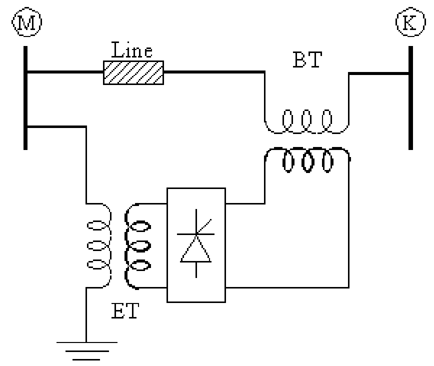

Fig. 4. Schematic diagram of a TCPS lag controller and with PID

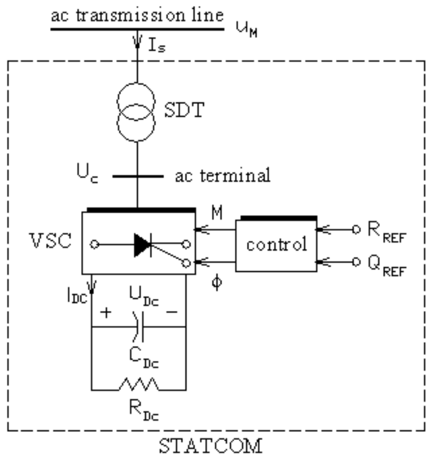

Fig. 5. Schematic diagram of an STATCOM

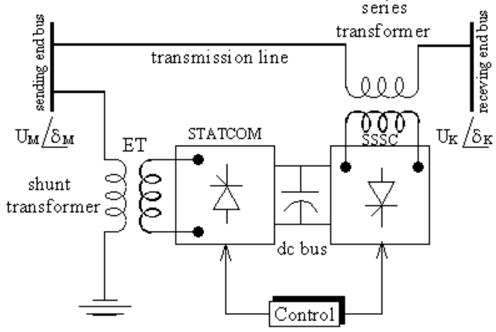

Fig. 6. Schematic diagram of an UPFC

c) IPFC and PSS: The IPFC can facilitate a comprehensive overall real and reactive power management for a multi-line transmission system. An IPFC is a FACTS device that compensates two or more lines simultaneously; it inserts a series voltage into each compensated line by applying a VSC. It is realized by two VCSs, which are in fact SSSCs, connected by a common DC link [55, 56]. IPFC connected in two parallel lines results in positive resistance in one line and a negative resistance in the other line.

Fig. 7 shows the schematic diagram of an IPFC [57]. The bacterial foraging algorithm to tune the parameters of the IPFC control signals in the nonlinear optimization process in a SMIB power system has been used in [58]. A simultaneous design of PSS and IPFC has been investigated in [59] by using PSO algorithm to optimize the stabilizers in a single machine power system.

d) SSSC and PSS: SSSC can be used for series compensation of transmission lines. The SSSC is based on a dc capacitor fed voltage source inverter that generates a three-phase voltage at fundamental frequency, which is then injected to a transmission line through a transformer connected in series with line [60]. The SSSC has three modes of operation: 1) constant voltage mode, 2) constant impedance emulation mode, and 3) constant power control mode [61]. If SSSC voltage is function of the transmission line current, the SSSC operates in constant reactance mode and when the SSSC voltage is independent of the line current, the SSSC operates in constant quadrature voltage mode [62]. A SSSC is installed on the transmission line between nodes 1 and 2 as shown in Fig. 8.

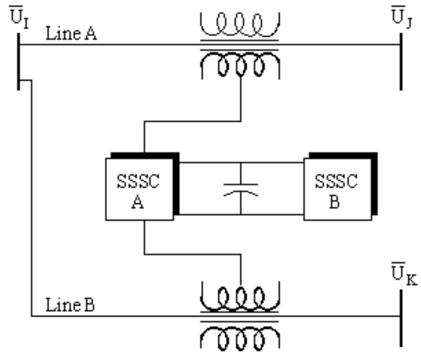

Fig. 7. Schematic diagram of an IPFC

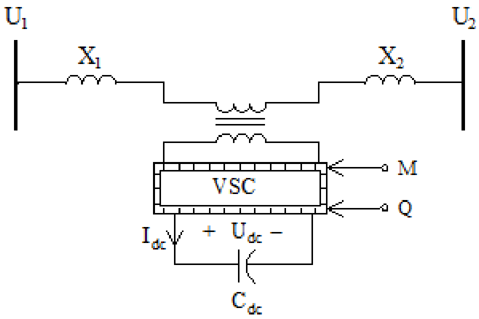

Fig. 8. Basic structure of an SSSC

A hybrid PSO and gravitational search algorithm is used in order to improve the power system stability, by designing a coordinated structure composed of a PSS and SSSC-based damping controller presented in [63]. A method for the simultaneous coordinated design of a PSS and a SSSC-based stabilizer is presented in [64] using quadratic mathematical programming in which the gain and phase of a lead-lag stabilizer can be simultaneously calculated. The extent and nature of control interaction between a PSS and a SSSC is studied in [65], in which the SSSC is used as a fixed compensator and the dc-link voltage of the SSSC is regulated by a simple PI controller.

C. Hybrid devices and PSS

There are two main types of hybrid FACTS devices: 1) Fault current limiter and 2) STATCOM energy storage [66].

a) STATCOM energy storage and PSS: The combination of a STATCOM with superconducting magnetic energy storage (SMES) is one of the most effective stabilizers of power oscillation modes [67, 68]. SMES systems can provide improved dynamic stability, enhanced power quality and area protection [69, 70]. The STATCOM with energy storage function (ESTATCOM) is represented by a current source for both active (I_P) and reactive (I_Q) compensator. The damping controllers of the active and the reactive current control the output of each current source separately. As shown in Fig. 9, the voltage deviation signal ΔU_M, at the bus where ESTATCOM is connected and the active power flow deviation signal ΔP_L, on the transmission line were considered as input signals [71]. Adding active power injection capability to the STATCOM by connecting an energy storage to the dc-link of the converter (E-STATCOM) can provide additional damping and improve the stability of the power system. The impact of the location of the E-STATCOM on its dynamic performance is typically not treated [72].

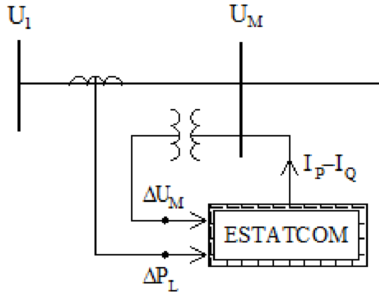

Fig. 9. Schematic diagram of an ESTATCOM

b) Fault current limiter and PSS: A fault current limiter (FCL) is a device that limits the prospective fault current by generating impedance when a fault occurs in a power transmission network. It reduces fault currents to a lower manageable level and makes possible the use of lower rated protective devices. The term includes superconducting devices and non-superconducting devices [73, 74]. FCL installed in series with transmission line can just operate during the period from fault occurrence to fault clearing; FCL cannot control the generator disturbances after the clearing of fault [75]. Various types of fault current limiters have been developed recently. They are categorized into the following three broad types: 1) the resistive type, 2) the inductive type and 3) bridge type SFCL [76].

V. CONCLUSION

PSS and FACTS devices can help to enhance the damping of power oscillations. Uncoordinated FACTS devices and PSS always cause interactions between the generators and controllers. A comprehensive literature review of the PSS and FACTS devices was carried out. A detailed survey on the topic of coordination of FACTS controllers and PSS used for dynamic performance improvement in single-machine and multi-machine power system was carried out.

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