

REVIEW OF POWER SYSTEM STABILIZER: APPLICATION, MODELING, ANALYSIS AND CONTROL STRATEGY

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Abstract- A Power System Stabilizer (PSS) is the most cost effective approach of increase the system positive damping, improve the steady-state stability margin, and suppress the low-frequency oscillation of the power system. A PSS has to perform well under operating point variations. Some of the major issues in the application of PSS are the choice of the input signal, the location of the PSS, the control algorithms and coordination with flexible AC transmission system (FACTS) devices. This paper presents an exhaustive review of power system stabilizer in terms of operation, dynamics, and control technique. It also reviews various methods for optimal placement of PSS. Studies have shown that PSS are designed to provide additional damping torque without affecting the synchronizing torque at critical frequencies in order to improve power system dynamic stability.

Keywords: Power System Stabilizer (PSS), Flexible AC Transmission System (FACTS), Single-Machine Infinite-Bus (SMIB).

I. INTRODUCTION

Power system dynamic performance is improved by the damping of system oscillations. Generally, there are two kinds of power oscillation damping controllers in power systems: PSS and FACTS controllers [1-5]. PSS is widely used in the electric power industry for improve the performance and functions of power systems during normal and abnormal operations. It can increase the system positive damping, improve the steady-state stability margin, and suppress the low-frequency oscillation of the power system [6-12]. Design and application of PSS has been the subject of continuing development for many years. All part of the PSS topic are numerous and various.

These are classified as: (a) mathematical modeling and proper signal selection, (b) finding the optimal placement of PSS, (c) coordination between the PSS and the FACTS, (d) the optimal parameters of the controller, and effect of PSS on system stability [13-21]. A field test to adequately assess the oscillation damping effectiveness of the PSS in a multi-generator power plant is presented in [22], which the test allows estimating the location of

the dominant open-loop poles from frequency response measurements of the closed-loop multivariable system. The conic programming is an effective tool to solve robust PSS design problems by simultaneously considering several operating scenarios is show in [23].

Optimal multi-objective design of robust multi-machine power system using Genetic Algorithms is presented in [24], which a conventional speed-based lead-lag PSS is used. A method based on a model predictive control for robust tuning of PSS and AVR in multi-machine power systems to improve the stability of the wide-area power system with distribution systems including dispersed generations is presented in [25].

This paper will review some of the published work in application, operation and control technique of PSS. The principle of operation of PSS such as input signals and block diagram is described in section II. The Multi-Band PSS (MB-PSS) is described in section III. Section IV provides an overview of the conventional techniques of controllers to enhance performance of a PSS. Section V presents the review of various methods for selecting the PSS location in multi-machine power systems.

A detailed overview of the modes oscillations is presented in section VI. The effects of PSS on the Sub-Synchronous Resonance (SSR) damping characteristics show in section VII. FACTS devices and PSS can help the damping of power system oscillations. The basic concepts of coordination between PSS and FACTS devices have been presented in section VIII. In power system stability, the damping torque and the synchronous torque are both important. Section IX covers the mathematical modeling of the single-machine infinite-bus (SMIB) installed with PSS. Section X presents the summary and the conclusions of the paper.

II. SUPPLEMENTARY EXCITATION

The idea of supplementary excitation is to apply a signal through the excitation system to increase the damping torque of the generator in a power system. Power System Stabilizer (PSS) is used to generate supplementary control signals to excitation systems in order to dampen the low frequency oscillations.

A. Excitation System

Figure 1 shows the functional block diagram of a typical of a large synchronous generator. Fast acting exciters with high gain AVR (Automatic Voltage Regulator) gives good voltage control and increases the possibilities of keeping the generator synchronized at large disturbances, but can contribute to oscillatory instability in power systems.

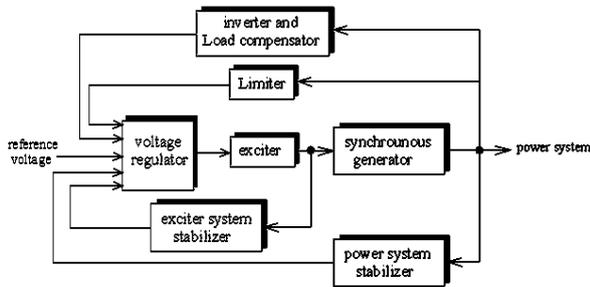


Figure 1. Block diagram of synchronous generator excitation system and structure diagram of power system stabilizer

The objective of PSS control is to directly target the control of the generator. Therefore, the PSS control is a direct control on the generator side.

B. Input Signals

A PSS can be viewed as an additional block of a generator excitation control or automatic voltage regulator, added to improve the overall power system dynamic performance, especially for the control electromechanical oscillations. The input signal for the PSS in the system is a point of debate. The input signals that have been identified as valuable include deviations in the shaft speed, the accelerating power, the terminal frequency and the active power output and linear combinations of these have been extensively investigated and recommendations regarding their use have been reported in the literature [26-32]. Since the main action of the PSS is to control the rotor oscillations, the input signal of rotor speed has been the most frequently advocated in the literature.

One of the limitations of the speed input PSS is that it may excite torsional oscillatory modes. It is important to select the PSS parameters carefully depending on its input signal and location in the power system [33, 34]. In [35], an indirect adaptive PSS is designed using two input signals, the speed deviation, and the power deviation to a neural network controller. A design method for PSS using the power flow of a remote transmission line and a remote bus voltage is proposed in [36], which it was possible to improve the damping of inter-area oscillations and the power transfer capability.

C. Block Diagram

A PSS model is viewed as an additional control block to enhance system stability. To provide damping, PSS must produce a component of electrical torque in phase with the rotor speed deviations. Controllers based on speed deviation would ideally use a differential type of regulation and a high gain, a typical PSS block diagram is

shown in Figure 2 [37]. It consists of an amplifier block of gain constant K_P , a block having a washout time constant T_w and one or two lead-lag compensators. The output signal of PSS is a voltage signals here it is U_s [38-40]. In practice, two or more first-order blocks can be used to achieve desired phase compensation.

It is accomplished by adjusting the PSS to compensate for phase lags through the generator, excitation system, and power system, such that PSS provides torque changes in phase with speed changes. The signal washout block serves as high pass filter, which remove any DC offsets in output of PSS in steady state. Without it, steady changes in speed would modify the terminal voltage [41, 42]. Controllers based on speed deviation would ideally use a differential type of regulation and a high gain. Since this is impractical in reality, the previously mentioned lead-lag structure is commonly used. The gain and the lead-lag compensator time constants are to be selected for optimal performance over a wide range of operating conditions. All of the variables of the PSS must be determined for each type of generator separately because of dependence on machine parameters.

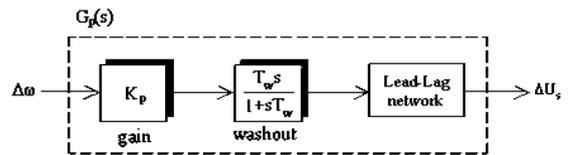


Figure 2. Block diagram of general power system stabilizer [37]

III. MULTIBAND PSS

The need for improving the damping of a wide range of electromechanical oscillations motivated the concept of the multiband PSS. Its structure is based on multiple working bands. As for conventional PSS, the MB-PSS with three kinds of frequency bands action function are used, dedicated to low, intermediate, and high frequency modes of oscillations [43-45].

IV. CONTROL TECHNIQUES

Two of the most important factors for selecting a control technique are valid in a wide range of operating conditions and unexpected equipment failures [46]. The proper selection of PSS parameters to accommodate variations in the power system dynamics is important [47]. The parameters of the excitation system and PSS are chosen to enhance the overall system stability [48]. The PSS design methods can be divided into three categories [49]: (a) linear control methods such as pole placement [50], linear quadratic regulation [51], eigenvalue sensitivity analysis and sliding mode control, (b) nonlinear control methods [52] such as adaptive control [53], fuzzy logic, and (c) empirical control methods such as artificial intelligence techniques [54, 55].

PSS has to perform well under various loading conditions and stability of system is guaranteed [56, 57]. Robustness of a PSS is a major issue [58]. Many robust control techniques have been used in the design of PSS. Some of major approaches to robust control are

H-infinity optimal control, structured singular value, parameter space method, pole placement, Quantitative Feedback Theory (QFT) [59], Variable Structure Control (VSC) and Linear Matrix Inequality (LMI) [60, 61]. Generally, PSS control design methodologies can be categorized as (a) classical methods, (b) adaptive and variable structure methods, (c) robust control approaches, (d) artificial intelligent techniques and (e) digital control schemes.

A. State Feedback Control

The state feedback power system stabilizers possess superior control capabilities when compared to the conventional lead-lag power system stabilizers [62]. They require feedback of all the state variables, which are generally not measurable [63]. However, in this method robustness may not be always possible. The design of robust PSS base on full state feedback, which place the system poles in an acceptable region in the complex plane for a given set of operating, and system conditions is presented in [64]. In [65], Hybrid Differential Evolution (HDE) has been used to investigate a decentralized pole placement design method of output feedback PSS, which HDE method is originally an optimal searching approach.

B. Particle Swarm Optimization

The Particle Swarm Optimization (PSO) technique belongs to class of evolutionary programming approaches for optimization. It is computationally simple since it neither requires gradient calculations nor necessitates the convexity of the function to be optimized [66]. A modified PSO algorithm with a small population for the design of optimal PSS used to determine the optimal parameters of several PSS simultaneously in a multi-machine power system is presented in [67].

A simultaneous coordinated design of the Thyristor Controlled Series Capacitor (TCSC) damping controller and PSS in multi-machine power system is presented in [68], which the optimization problem with the time domain-based objective function is solved by a PSO technique which has a strong ability to find the most optimistic results. A method based on the PSO algorithm, based on the optimization of a suitable objective function, for tuning PSS parameters is presented in [69], which optimal values for PSS controlling parameters including lead-lag compensator time constants as well as the controller gain are calculated.

C. Adaptive and Variable Structure Method

The power systems are complex and highly nonlinear systems. The linearized system models are valid only at the operating point that is used to linearize the system. If the parameters of the stabilizer are kept fixed, PSS performance is degraded whenever the operating point changes [70-74]. The basic function of adaptive control is to adjust the parameters, in real time and according to the behavior of the power system and provided good damping over a wide operating range [75]. All adaptive control techniques can be divided into two different groups, Direct Adaptive Control (DAC) and Indirect

Adaptive Control (IAC). In DAC such as Model Reference Adaptive Control (MRAC) the controller parameters are adjusted, so that the output of the controlled system to follow the output of a reference model. In IAC such as self-tuning control, the aim is to control the system so that its behavior has the given properties [76].

In comparison with the self-tuning control, MRAC has some advantages, such as fast adaptation process and lower computing complexity of adaptation algorithm [77]. The damping effects of an adaptive PSS by simulations and compared its damping effect with a conventional PSS in both time domain and frequency domain is studied in [78]. An adaptive PSS estimates some uncertainty within the system, and then automatically designs a controller for the estimated plant uncertainty [79]. An adaptive PSS consisting of an online-identified plant model and self-learning fuzzy logic controller, for PSS application is described in [80].

Application of a neural adaptive PSS to a five-machine power system is described in [81], which the proposed technique comprises two sub networks: the 'Adaptive Neuro-Identifier' to dynamically identify the nonlinear plant, and the Adaptive Neuro-Controller to damp output oscillations. An adaptive PSS, which consists of a recurrent neural network controller to supply an adaptive control signal to the exciter or governor with the adaptive law and a compensator to damp the oscillations of power system, is presented in [82]. An indirect adaptive fuzzy PSS used to damp inter-area modes of oscillation following disturbances in power systems is proposed in [83], which the gains of the controller are tuned via a PSO routine to ensure system stability and minimum sum of the squares of the speed deviations.

D. Artificial Intelligent Techniques

Artificial Intelligence Techniques are Artificial Neural Network (ANN), Fuzzy Logic, Intelligent Optimization, Hybrid Artificial Intelligent Techniques and Expert System [84, 85].

The application of fuzzy logic control has been motivated by following reasons: (a) improved robustness over conventional linear control algorithms, (b) simplified control design for difficult system models, (c) simplified implementation [86]. A fuzzy logic based adaptive PSS is proposed in [87], which neural networks online tune the parameters of fuzzy logic based PSS. An approach based on Traditional Frequency Domain method for designing fuzzy logic based adaptive PSS for multi-machine power systems is presented in [88]. The optimal design of settings of PSS parameters that shift the system eigenvalues associated with the electromechanical modes to the left in the S-Plane using Evolutionary Programming Optimization technique is presented in [89].

The systematic optimal tuning of all parameters PSS based on the Hessian Matrix estimated by Feed-Forward Neural Network and the Eigenvalue analysis for the linear parameters is presented in [90], which can improve

the system damping performance immediately following a large disturbance. In [91], the simultaneous stabilization of a power system over a wide range of operating conditions via a single-setting conventional power system stabilizer using GA is investigated.

E. H-Infinity Control

It cannot provide good transient behavior. In addition, design is complex because of dynamic output feedback. In robust control theory, H_2 performance and H_∞ performance are two important specifications. In [92], the effectiveness of the power system stabilizer designed through weighted mixed sensitivity H_∞ robust control theory is demonstrated by simulation of a sample power system for various load conditions using MATLAB. In [93] an H_∞ optimal control method is design for PSS using a nominal model with an uncertainty description which represents the possible perturbation of a synchronous generator around its normal operating point. A method of designing H_∞ loop shaping based robust PSS for a dynamic equivalent large power system is presented in [94], which the simulation show that it very effectively.

F. Linear Matrix Inequality

Linear Matrix Inequality (LMI) is flexible in controller design since it provides an incredibly powerful way to solve convex or quasi-convex optimization problems. It is the way to specify system dynamic performance. In [95], the robust control using fuzzy controller is designed by satisfying certain LMI conditions, to improve the angular stability at multiple operating points. A H_2 controller design approach for PSS based on LMI pole constraints analysis for damping low frequency oscillations is presented in [96], which the H_2 robust control guarantees the damping performance for different operating conditions and its robustness is better than that of conventional PSS. In [97], a mixed H_2/H_∞ control that is solved using LMI technique is used as a PSS for a SMIB system, which proposed controller show robustness over a wide range of operating conditions and parameters change.

G. Sliding Mode Controls

The parameters of a power system are varied continuously according to the conditions of the generation system, networks, and the load. In Sliding Mode Control (SMC), the parameter insensitivity and the realization simplicity, it is very robust [98]. The main disadvantage in SMC are: (a) stability is dependent on the sampling period when implemented using digital controllers, (b) full state-feedback structure may not be available at all times, and (c) limitation on amount of parameter variations [99].

In [100], a Neural Networks based Adaptive Sliding Mode Controller has been applied to a PSS of a single machine power system, which Neural Networks are used for online prediction of the optimal SMC gains when the operating point changes. In [101] a model reference discrete time Sliding Mode Controller for design of the

PSS is presented, which a number of studies demonstrates the effectiveness of the proposed approach. A PSS for a small-signal stability study using three kinds of controllers to solve the problem of the immeasurable state variables in the conventional sliding mode control is presented in [102], which the effectiveness of the proposed controller is verified by linear time-domain simulation under normal load operation and under parameter variation of AVR gain.

V. PSS OPTIMAL LOCATION

A PSS on a machine in a power system represents a closed-loop controller. The first step in designing such a PSS to increase the damping of a certain oscillation mode in a multi-machine power system is to find its optimum location. The PSS is important to quickly damping the inter-area oscillations [103, 104]. The probabilistic approach for the optimum location of power system stabilizers is presented in [105], which the probabilistic distribution of an eigenvalue is expressed by its expectation and variance under the assumption of normal distribution. Local controllers for machines that need to have stabilizers have been designed in [106], which by using sensitivity analysis, the relation between system states and oscillatory modes is considered.

VI. OSCILLATION MODES

Power system dynamic performance is improved by damping of system oscillations. The small-signal stability of the following types of electromechanical oscillations is of concern [107]: Local Modes, Inter-Area Modes, Control Modes and Torsional Modes.

The PSS are designed mainly to stabilize local and inter-area modes [108]. By varying the terminal voltage, the PSS affects the power flow from the generator, which efficiently damps local modes. Damping of both local and Inter-Area modes requires suitable phase compensation over a wider frequency range, which may be difficult to achieve. Proper tuning and coordination of multiple PSS controller can adequately damp out oscillations with any local rotor angle oscillatory modes [109]. Dynamic stability enhancement of electromechanical modes of multi-machine power systems by means of an adaptive PSS is proposed in [110], which it is a variational configuration to self-adjusted tracking system operation condition.

A method based on modal decomposition for tuning PSSs for damping of the concerned inter-area mode is proposed in [111], while minimizing its effect on other modes by weakening the interactions among different modes. An extended quasi-steady-state model of long-term dynamics that includes low-frequency inter-area oscillations can be used effectively for the design of PSS is show in [112], which all local and intra-area electromechanical oscillations are replaced in this model by algebraic equations.

VII. EFFECT OF PSS ON SSR

SSR is an electromechanical power system instability, which occurs due to interaction between series capacitors and nearby turbine-generators. It can break generator shafts and must be studied and prevented when series compensation is used [113, 114]. The PSS keep the power system in a secure state and protect it from dangerous phenomena [115, 116]. The effects of different types of excitation systems and PSS on the SSR damping characteristics in a SMIB system are studied in [117], which the effects of the parameters of PSS on the electrical damping are investigated. A LQR based-PSS to control the SSR presented in [118], which eigenvalue analysis and time domain simulations using a nonlinear system model show that proposed PSS can control the SSR efficiently. The behavioral aspects of two types of PSS in [119] are studied in a fixed series capacitor compensated system employing the IEEE first benchmark system for SSR study.

VIII. PSS AND FACTS DERIVES

Electromechanical oscillations of small magnitude and low frequency exist in the interconnected power system and often persist for long periods of time [120]. PSS and FACTS devices are applied to increase the system stability and improve system performance [121]. They can help the damping of power system oscillations. PSS increases damping torque of a generator by affecting the generator excitation control, while FACTS devices improve damping by modulating the equivalent power-angle characteristic of the system [122, 123].

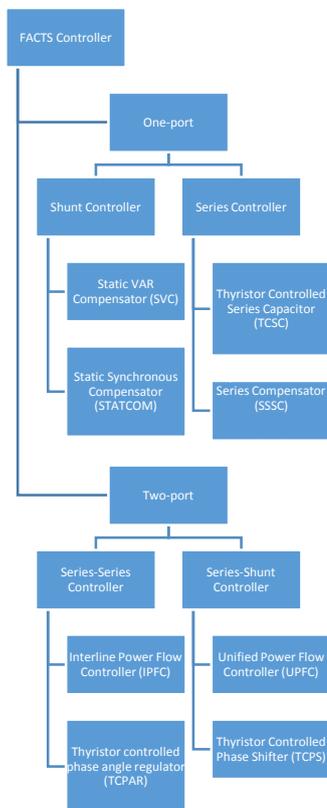


Figure 3. Overview of compensation devices [1]

There are several methods proposed in literatures on coordination between PSS and FACTS devices, in multi-machine power systems from different operating conditions viewpoint [124-131]. Several kinds of FACTS-devices have been developed [132-134]. It can be divided into two categories as shown in Figure 3 [135, 136]. In general, from control of view, FACTS controllers can be divided into four categories: Series Controllers, Shunt Controllers, Combined Series-Shunt Controllers, and Combined Series-Series Controllers.

A. Shunt Controller and PSS

An optimal designing method, which is based on adaptive genetic algorithm, is applied in the cooperation control of PSS and STATCOM proposed in [137], that simulation results show the stability of power angle and voltage can be effectively enhanced. A systematic approach for designing of SVC based damping controllers for damping of low frequency oscillations in a SMIB power system is presented in [138].

B. Series Controller and PSS

The tuning of Proportional Integral Derivative (PID) PSS and TCSC is studied in [139], which the Genetic Algorithm (GA) is used to search for optimal settings of controller parameters. An output feedback controller for PSS and TCSC based on genetic algorithm in order to damp the low frequency oscillations in a single machine infinite bus is design in [140], which TCSC located at the terminal of generator, is considered. Based on multivariable model, and by using the concept of the minimization of column dominance measure, a multi-input multi-output controller is designed in [141] to minimize interaction among the control variables of PSS and Series Static Synchronous Compensators (SSSC).

C. Series-Shunt Controller and PSS

A control scheme to design an advanced PSS, comprehensive analysis, and result obtained for the dynamic control of power transmission, damping of oscillations with Unified Power Flow Controller (UPFC) presented in [142]. The study and design a controller capable of doing the task of damping in less economical control effort for coordination between PSS and thyristor controlled phase shifter (TCPS) is presented in [143].

D. Series-Series Controller and PSS

In [144], fuzzy logic controller by selecting effective control signal based supplementary controller is installed with Interline Power Flow Controller (IPFC) to damp low frequency oscillations.

IX. SINGLE-MACHINE INFINITE-BUS

Numerous different control techniques, which are based on classical or optimum control techniques, have been applied to design PSS but many of them are use a linearized model of an electrical machine connected to a power system. The basic block diagram of power system linear model is show in Figure 4 [145], where K_1 and K_2 are the constant derived from electrical torque, K_3 and K_4

are the constant derived from field voltage equation, and K_5 and K_6 are the constant derived from terminal voltage magnitude [146]. The electrical torque can represent as:

$$\Delta T_E = \Delta T_{E1} + \Delta T_{E2} = \underbrace{[K_1 + H_Q(s) + H_P(s)]}_{H_E(s)} \Delta \delta \quad (1)$$

The action of the PSS is effective through the transfer function block between the electric torque output and the reference voltage input with variation in the machine speed assumed to be zero [147-149].

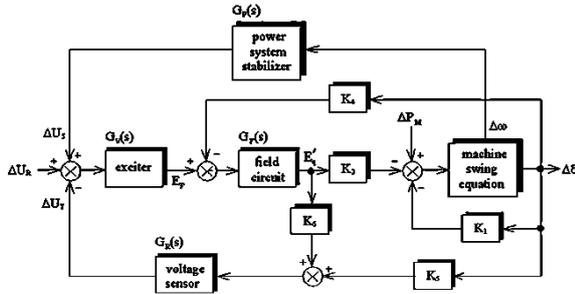


Figure 4. Block diagram of SMIB system [145]

The main objective of designing PSS is to increase the damping torque without affecting the synchronizing torque at critical frequencies. To provide damping, PSS must produce a component of electrical torque in phase with the rotor speed deviations [150, 151]. The K_S and K_D are synchronizing torque and damping torque is defined:

$$K_S(\omega) = \text{Re}[H_E(j\omega)] \quad (2)$$

$$K_D(\omega) = \frac{\omega_b}{\omega} \text{Im}[H_E(j\omega)] \quad (3)$$

In small oscillations, the damping torque in phase with $\Delta\omega$, and the synchronous torque is in phase with $\Delta\delta$. They are sensitive to generator operating conditions, parameters of power system network, excitation system and PSS parameters [152]. The block diagram representing the small signal stability model can be simplified as shown in Figure 5, where the transfer functions $H_Q(s)$ and $H_P(s)$ are defined as:

$$H_Q(s) = -\frac{K_2 G_F(s) [K_4 + K_5 G_V(s) G_R(s)]}{1 + K_6 G_V(s) G_F(s) G_R(s)} \quad (4)$$

$$H_P(s) = \frac{K_2 G_V(s) G_F(s) G_P(s)}{1 + K_6 G_V(s) G_F(s) G_R(s)} \frac{s}{\omega_b} \quad (5)$$

$$H_P(s) = \frac{s}{\omega_b} G_E(s) G_P(s) \quad (6)$$

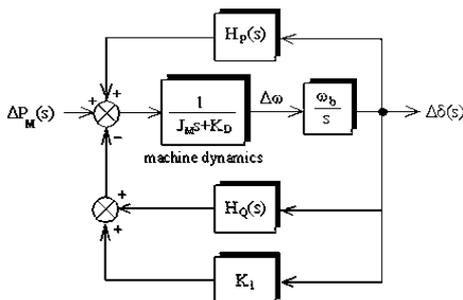


Figure 5. System transfer function model

The control transfer function of excitation system as shown in Figure 6.

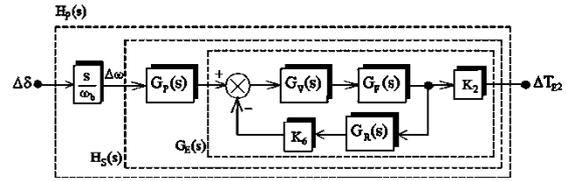


Figure 6. Control block diagram of excitation system

where $G_E(s)$ is the transfer function of the electrical loop between the incremental terminal voltage (ΔU_s) and the internal voltage variation ($\Delta E'_q$). The effects of PSS on synchronizing and damping torque components are defined as [153, 154]:

$$K_{s(PSS)}(\omega) = \text{Re}[H_P(j\omega)] \quad (7)$$

$$K_{d(PSS)}(\omega) = \frac{\omega_b}{\omega} \text{Im}[H_P(j\omega)] \quad (8)$$

X. CONCLUSIONS

This paper presents a critical review of the recent philosophies in the area of PSS. A simple, economical and effective for improve the steady-state stability margin, increase system positive damping, suppress low-frequency oscillation of the power system and improve power system dynamic stability is with PSS. It has been widely used in the electric power industry in order to increase the damping ratios of electromechanical modes, extend power transfer limits of system and maintain the reliable operation of the grid.

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