Damping low-frequency oscillations in a Multi-machine Power System using a Fuzzy-Multi-Band Power System Stabilizer

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Abstract

Synchronous generators are usually equipped with power system stabilizers (PSS) to damp low-frequency oscillations. Among the various types of PSS, it has recently been demonstrated that the Multi-Band PSS (MB-PSS) has a better performance to handle all global, inter-area and local modes. However, the performance of this PSS may degrade since the power supply system is intrinsically non-linear and its operating conditions frequently change. This paper introduces a new design of MB-PSS based on Mamdani Fuzzy inference (Fuzzy-MB-PSS). Compared to the IEEE standard MB-PSS, the proposed stabilizer is more efficient owing to its ability to deal with oscillations at different operating points. The controller is tested on a power system benchmark under various disturbance conditions to prove its robustness and to demonstrate its superiority over conventional PSS and MB-PSS.

Keywords: Power system stability, low-frequency oscillations, Fuzzy-MB-PSS.

1. Introduction

Power system stability is a major concern for system operational studies since it is easily influenced by internal and external disturbances of synchronous machines [1]. Modern power systems today, can attain critical conditions faster than in the past due to energy demand increase. It is consequently necessary to enhance the system stability margin by employing supplementary regulators [2].

Power systems are frequently undergoing low-frequency oscillations: inter-area modes (0.16 to 0.7 Hz) and local modes (0.7 to 2 Hz) [3]. If these later are not adequately damped, they will severely affect the power system security and stability and may even result in a cascade failure with serious implications.

One of the most effective techniques that have proven its ability to dampen oscillation modes is the use of the Power System Stabilizer [4]. The primary function of PSS is to provide supplemental damping to both oscillation types and to improve the power system overall stability over a wide set of operating conditions and disturbances [4].

Conventional PSSs (CPSSs) are usually designed using a linear model. However, as the topology of the power system and the loads change continuously, the CPSS cannot operate effectively to dampen all modes, especially the inter-area ones [5]. To cope with this problem and to have a robust CPSS, various studies have been conducted in recent years. These researches are generally classified into two categories: (i) the development of a new method for CPSS parameters setting and (ii) the development of a new PSS structure [6]. The first category introduces new methods for PSS setting to ensure sufficient damping of low-frequency oscillations for different operating conditions. These methods include lead-lag based regulators, adaptative and non-linear control algorithms, robust control methods and artificial intelligence approaches [7, 8, 9, 10]. Furthermore, methods based on meta-heuristic and evolutionary computation have recently attracted more attention in solving power system optimization problems. The most common approaches to overcome the deficiencies of CPSS tuning are Bacterial foraging algorithm (BFA), particle swarm optimization (PSO), chaotic optimization algorithms (COA), ant colony optimization and genetic algorithm (GA) [11, 12, 13, 14].

The second category focuses on finding a new PSS structure to improve the CPSS performance like classical PID-PSS, algebraic-PSS, multi-input PSS, and MB-PSS [14, 15, 16]. Moreover, tremendous efforts have been devoted to the development of adaptive PSS [14, 16]. The basic idea of adaptive techniques is to assess the uncertainties of online plants based on measured signals [14]. However, adaptive PSSs are not able to exploit the human experience that is expressed in linguistic descriptions. This limitation is overcome through the use of artificial intelligence techniques (fuzzy logic, neural networks, and decision trees) in the design of PSS [11, 17, 18]. Fuzzy systems are generally considered appropriate for controlling systems since they are model-free approaches that are based on a set of linguistic rules [19]. In fuzzy command, the controller is derived from a series of fuzzy "If-Then" rules that describe the unknown power station behaviour. Fuzzy logic systems insure the non-linearization of an input data vector space into an output space scalar, which is generally enough to permit systems control and identification [12]. In [6], authors have examined the impact of the RES based MG on the dynamic stability and the control of a multi-machine and multi-area system under varying operating conditions. A new type-2 fuzzy fractional-order PSS based on a hybrid meta-heuristic algorithm has been introduced to improve the damping performance of electromechanical oscillations of the power system to increase the dynamic stability of the power system. A multi-fractional multi-band power system stabilizer (MF-MBPSS), for small-signal stability and frequency response improvement in closed-loop control, has been presented in [20].

Nomenclature

δ - the rotor angle;
ω - the rotor speed;
P_m - the mechanical power;
$M = 2H$ - the acceleration time constant;
D - the damping coefficient;
$T_{d0}^{'}, T_{d0}^{''}, T_{q0}^{'}, T_{q0}^{''}$ - the dq-axes transient and sub-transient open-circuit time constants;
$e_d^{'}, e_q^{'}, e_d^{''}, e_q^{''}, x_d^{''}, x_q^{''}$ - the dq-axes transient and sub-transient open-circuit voltages;
$x_d, x_q, x_d^{'}, x_q^{'}, x_d^{''}, x_q^{''}$ - the dq-axes steady-state, transient and sub-transient reactance's;
i_d, i_q - the dq-axes currents;
k_a, T_a - the excitation gain and time constant;
e_{fd}, V_{ref}, V_t - the excitation, reference and terminal voltages;
$\Delta\omega$ - the speed deviation in p.u.

Authors in [21] have designed a fuzzy power system stabilizer based on Cuckoo Search Algorithm to damp power system oscillations.

Inward the last theme, a new design of MB-PSS based on Mamdani Fuzzy inference (Fuzzy-MB-PSS) is used to damp the multi-machine system low-frequency oscillations in this paper. The motivation behind this stabilizer model was that the lead/lag compensating filters in the CPSS could not give an accurate compensation over a wide range of oscillation frequencies. If the network suffers from low and high frequency oscillations, the tuning procedure of the single-band stabilizers have to compromise and will not achieve optimal damping in any of the oscillations. Thus, compared to the conventional PSS, the proposed Fuzzy-MB-PSS offers a more accurate compensation signal to the exciter in a wider range of frequencies. This makes the proposed control strategy more effective in electromechanical oscillation damping of a multi-machines system when exposed to external disturbances.

This paper is organized as follows. Section 2 describes the nonlinear dynamic model of a multi-machine power system. The Fuzzy-MB-PSS is introduced in Section 3. Section 4 illustrates the simulation results under various disturbance scenarios in the test system along with a few discussions. Finally, the paper is concluded in Section 5.

2 Multi-machine power system

2.1. System characteristics

To show the effectiveness of the proposed method for improving power system dynamic stability, a 10- machines 39-bus system is considered for the study. The system is made up of 12 transformers, 34 transmission lines and 19 loads. The total active and reactive loads for the basic configuration are 6145.97 MW and 1363.41 Mvar, respectively. The voltage levels of the test system are 20 kV, 115 kV and 345 kV as shown in Figure Figure 1 with red, blue and black colors, respectively. The numerical investigations were performed using MATLAB/Simulink and all the data used for the system implementation are given in [22].

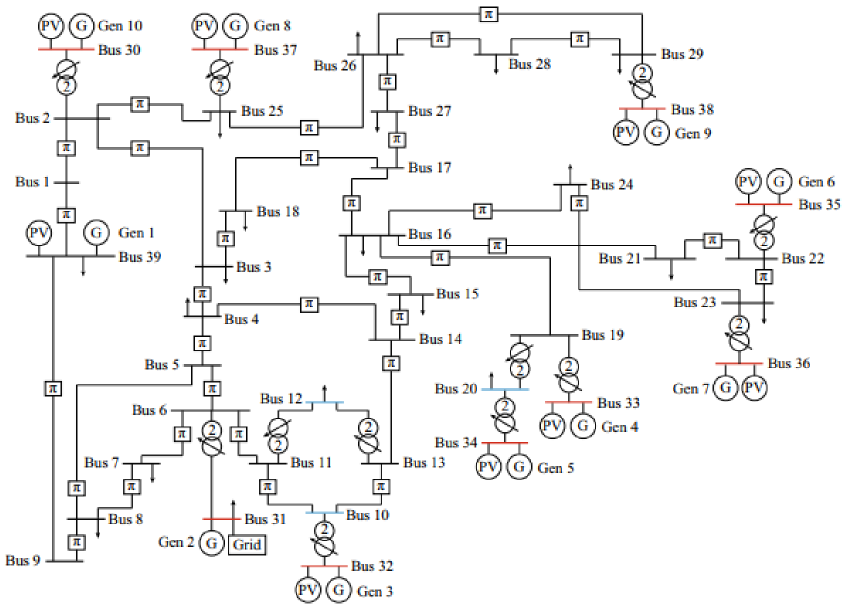

Figure 1: The single-line diagram of IEEE 39-bus power system

2.2. Dynamic modelling of the system

For dynamic stability analysis, a two-axis, six-order model is employed for simulating all generators. The dynamic characteristics of electrical systems can be modelled by a set of non-linear differential equations as:

$$\dot{x} = f(x, u) \quad (1)$$

where $x = [\delta, \omega, e_q^{'}, e_d^{'}, e_q^{''}, e_d^{''}, e_{fd}^{'}]^T$ is the state vector and u is the control input vector. The set of nonlinear differential-algebraic equations for the ith machine in the dynamic model of the multimachine system is given in (2).

$$\begin{cases} \dot{\delta} = \omega_0(\omega - 1) \\ M\dot{\omega} = P_m - e_q^{''} i_q - e_d^{''} i_d + (x_d^{''} - x_q^{''}) i_d i_q - D(\omega - 1) \\ T_{d0}^{'} \dot{e}_q^{'} = -e_q^{'} - (x_d - x_d^{'} - \frac{T_{d0}^{''}}{T_{d0}^{'}} \frac{x_d^{''}}{x_d^{'}} (x_d - x_d^{'})) i_d + e_{fd} \\ T_{q0}^{'} \dot{e}_d^{'} = -e_d^{'} - (x_q - x_q^{'} - \frac{T_{q0}^{''}}{T_{q0}^{'}} \frac{x_q^{''}}{x_q^{'}} (x_q - x_q^{'})) i_q \\ T_{d0}^{''} \dot{e}_q^{''} = -e_q^{''} + e_q^{'} - (x_d^{'} - x_d^{''} + \frac{T_{d0}^{''}}{T_{d0}^{'}} \frac{x_d^{''}}{x_d^{'}} (x_d - x_d^{'})) i_d \\ T_{q0}^{''} \dot{e}_d^{''} = -e_d^{''} + e_d^{'} - (x_q^{'} - x_q^{''} + \frac{T_{q0}^{''}}{T_{q0}^{'}} \frac{x_q^{''}}{x_q^{'}} (x_q - x_q^{'})) i_q \end{cases} \quad (2)$$

All synchronous machines are equipped with IEEE Type I excitation system model expressed by:

$$T_a \dot{e}_{fd} = K_a(V_{ref} - V_t) - e_{fd}. \quad (3)$$

3 Power system stabilizer

3.1. Conventional Power System Stabilizer (CPSS)

FigureFigure 2 shows the structure of the CPSS, where the input signal is the generator speed generally [22]. The mathematical formulation of the CPSS is as follows:

$$V_{PSS} = K_{PSS} \frac{ST_W}{1 + ST_W} \frac{1 + ST_1}{1 + ST_2} \frac{1 + ST_3}{1 + ST_4} \Delta\omega \quad (4)$$

The CPSS is composed of a gain K_{PSS}, a wash-out filter and, a dynamic compensator [22]. The wash-out filter is a high-pass filter with a time constant T_W employed to reinstate the steady-state offset in the PSS output. The dynamic compensator consists of lead-lag filters with leading time constants T_1 and T_2 lagging time constants T_3 and T_4. A voltage limiter with a range of V_{PSSmin} and $V_{PSSmax}$is placed at the end to prevent heavy saturation.

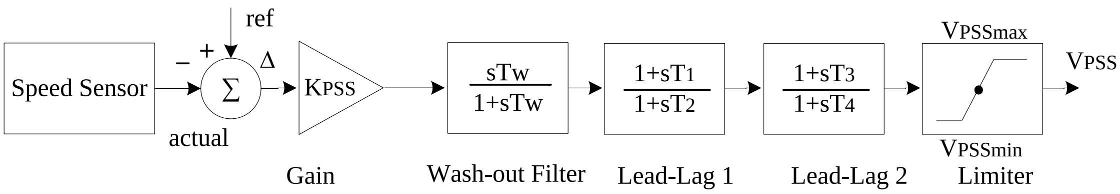

Figure 2: CPSS block diagram

3.2. Multi-Band Power System Stabilizer (MB-PSS)

The MB-PSS 4B structure which is based on several operating frequency ranges is depicted in Figure Figure 3. The latter includes three different frequency bands, low, intermediate and high. These signals are used to damp the global, inter-area and, local modes. Each of the three bands is made of a differential band-pass filter, a gain, and a limiter. The outputs of the three bands are summed and passed through a final limiter producing the stabilizer outputV_{ST}. This signal then modulates the set point of the generator voltage regulator to improve the damping of the electromechanical oscillations. Hence, the MB-PSS 4B with a flexible multi-band transfer function structure offers more freedom to implement a robust PSS over a wide frequency range under different contingency conditions. As stated previously, a new design of the MB-PSS based on Mamdani Fuzzy inference is introduced in this study where the structure details are presented in the next section.

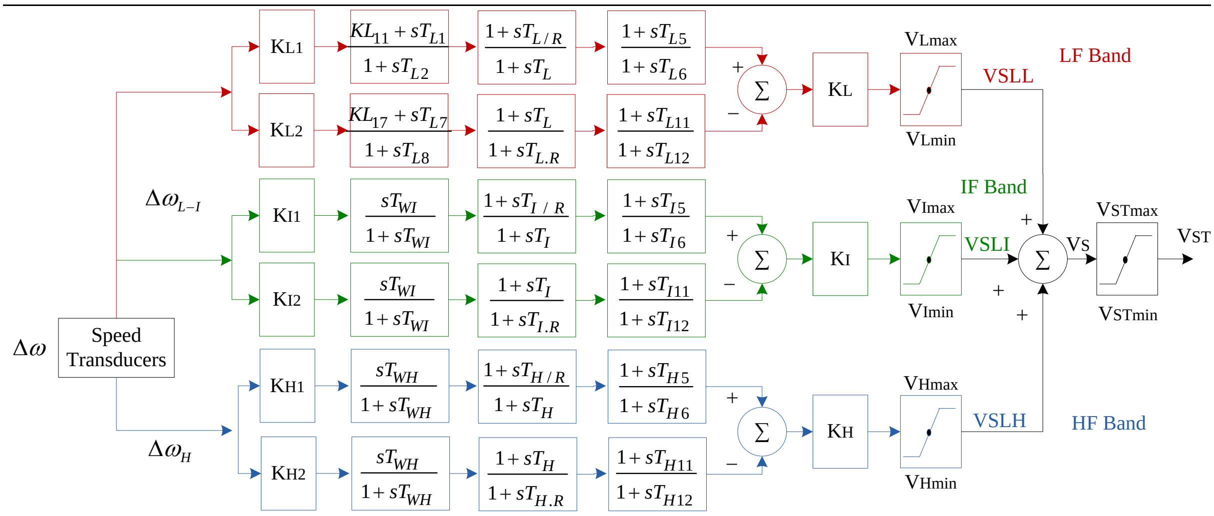

Figure 3: MB-PSS IEEE 4B block diagram

3.3. Proposed Fuzzy Multi-Band Power System Stabilizer (Fuzzy-MB-PSS)

Figure Figure 4 shows the proposed Fuzzy-MB-PSS design. As shown in this figure, the rotor speed deviation ($\Delta\omega$) and its derivative are used as inputs for fuzzy processing. The fuzzy control output is then injected into the MB-PSS. K_1 and K_2 are the scaling factors and K_3 is the normalization gain used to define the discourse universe and chosen according to the maximum value of the rotor speed error and it's derivative. The purpose of this stabilizer is to enhance the synchronous generator damping. To apply proper control, the proposed Fuzzy logic controller characteristics are: i) Seven fuzzy sets for: input and output variables which are defined as follows: Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (ZE), Positive Small (PS), Positive Medium (PM), Positive Big (PB). ii) The fuzzification process converts the numerical variable to a linguistic variable using a triangular membership function. iii) The Fuzzy inference is ensured by Mamdani Min-Max operator. iv) The defuzzification is established using the centroid method. The linguistic control rules are derived from the triangular membership function depicted in Figure Figure 5. The rules used in this paper are shown in Table Table 1.

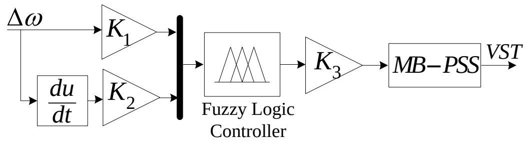

Figure 4: Fuzzy-MB-PSS

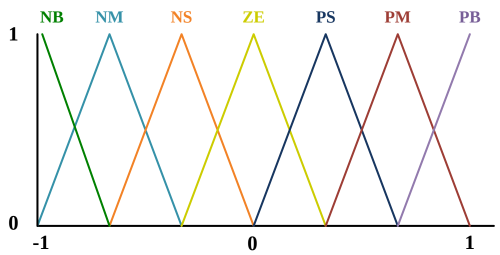

Figure 5: Membership Functions of Fuzzy Controller Input and Output variables

4 Simulation results and discussion

Here, optimization parameters are PI controller gains K_p and K_i , peak overshoot, rise time, settling time and steady-state error are the constraints that mean optimality of PI controller. Performance standard select in proposed research is integral square error (ISE) that make well both positive and negative errors uniformly. The objective function to be optimized is expressed as below:

Table 1: Rule base table

$\Delta\omega$ \ $\Delta\dot{\omega}$	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NM	NM	NS	ZE	PS
NM	NB	NM	NM	NS	ZE	PS	PM
NS	NB	NM	NS	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PS	PM	PB
PM	NM	NS	ZE	PS	PM	PM	PB
PB	NS	ZE	PS	PM	PM	PB	PB

In this section, the effectiveness and robustness of the proposed PSS for the multi-machine power system dynamic stability improvement is studied using a computer simulation process. A performance comparison is done on CPSS, MB-PSS and Fuzzy-MB-PSS to highlight the system dynamic response improvement and the relevance of the proposed PSS structure in achieving robustness. Moreover, for a system performance comprehensive study and analysis, four-fault disturbance scenarios are also treated:

• 1st fault disturbance: 10% step increase in the reference voltage of generator 2;

• 2nd fault disturbance: 30% step increase in the load at Bus 26;

• 3rd fault disturbance: Three-phase five-cycle fault in the line 15-16 at t=1s;

• 4th fault disturbance: Successive three-phase five cycle faults in the line 15-16 at t=1s and t=10s.

The rotor speed deviation of the most affected generator in each scenario is presented in Fig. Figure 6.

4.1. 10% step increase of generator 2 reference voltage

To assess the performance of the proposed Fuzzy-MB-PSS against small-signal disturbances, the reference voltage of generator 2 is increased by a 10% step at t=1s and removed after five-cycles. The rotor speed deviation of generator 2 is illustrated in Figure Figure 6 (a). This latter shows that CPSS and MB-PSS controllers provide the same damping results. On the other hand, despite the oscillations that the Fuzzy-MB-PSS presents, it gives a better dynamic performance in electromechanical modes damping in comparison with CPSS and MB-PSS. Still, the power system is intrinsically invariant to generator voltage variations.

4.2. 30% step increase in load at bus 26

For this simulation case, the disturbance is a 30% step load increase at bus 26. The results comparison, depicted in Figure Figure 6 (b), demonstrated that the generator 2 rotor speed, shows a more stable response when equipped with Fuzzy-MB-PSS. The latter is more efficient in damping out oscillations which proves its robustness and its ability to give less overshoot and fast rotor speed oscillations settling.

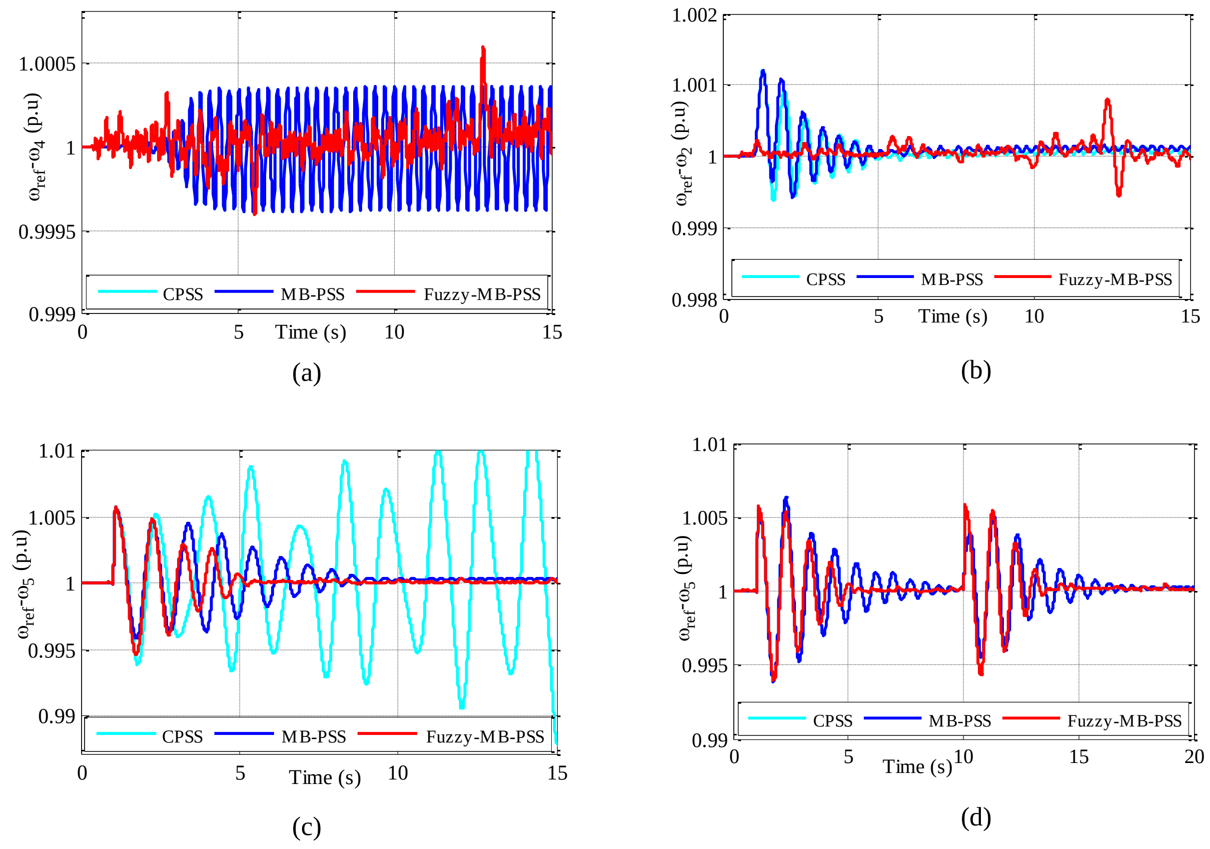

Figure 6: Dynamic response of the IEEE 39-Bus power system. (a) 10% step increase in reference voltage of generator 2,
(b) 10% step increase in load at Bus 26, (c) Three-phase fault in the line 16-15 at t=1s,(d) Successive three-phase faults in the line 16-15 at t=1s and t=10s

4.3. Three-phase fault in the line 15-16

To further ensure the performance of the proposed controller in treating large perturbations, a three-phase fault in the line 15-16 is applied at 1s and cleared after five-cycle. Figure Figure 6 (c) shows that, compared to the CPSS and the MB-PSS, the Fuzzy-MB-PSS can efficiently handle the power system electromechanical oscillations when the system is subjected to challenging large disturbances situations. Moreover, it can be noticed that MB-PSS presents better performance when compared to the CPSS.

4.4. Successive three-phase faults in the line 15-16

In this scenario, a three-phase fault in the line 15-16 is applied at 1s and cleared after five-cycle and then a second fault is applied at t=10s and suppressed after five-cycle. Figure Figure 6 (d) shows the power system electromechanical oscillations behavior after a successive three-phase fault in the line 15-16. The CPSS and the MB-PSS gives a similar performance for this scenario. In counterpart, it is clear from the simulation results that the Fuzzy-MB-PSS offers better damping of the electromechanical oscillations.

5 Conclusion

This paper proposes a robust power system stabilizer based on Mamdani fuzzy inference for multi-machine power system small signal stability enhancement. The comprehensive analysis shows that the Fuzzy-MB-PSS offers lower rotor speed fluctuations under all the considered operating conditions. Moreover, it is noticed that incorporating fuzzy inference in the MB-PSS structure gives better performance than the simple MB-PSS controller in the presence of disturbances and varying operating conditions. A comparative analysis with CPSS and MB-PSS is performed to further assess the performance of the proposed controller. This analysis proved that Fuzzy-MB-PSS outperforms both conventional controllers with an effective oscillation damping and settling time minimization.

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