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Power System Stabilizer Design Based on Model Reference Robust Fuzzy Control

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Abstract: Power System Stabilizers (PSS) are used to generate supplementary damping control signals for the excitation system in order to damp the Low Frequency Oscillations (LFO) of the electric power system. The PSS is usually designed based on classical control approaches but this Conventional PSS (CPSS) has some problems in power system control and stability enhancement. To overcome the drawbacks of CPSS, numerous techniques have been proposed in literatures. In this study a new method based on Model Reference Robust Fuzzy Control (MRRFC) is considered to design PSS. In this new approach, in first an optimal PSS is designed in the nominal operating condition and then power system identification is used to obtain model reference of power system including optimal PSS. With changing system operating condition from the nominal condition, the error between obtained model reference and power system response in sent to a fuzzy controller and this fuzzy controller provides the stabilizing signal for damping power system oscillations just like PSS. In order to model reference identification a PID type PSS (PID-PSS) is considered for damping electric power system oscillations. The parameters of this PID-PSS are tuned based on hybrid Genetic Algorithms (GA) optimization method. The proposed MRRFC is evaluated against the CPSS at a single machine infinite bus power system considering system parametric uncertainties. The simulation results clearly indicate the effectiveness and validity of the proposed method.

Key words: Low frequency oscillations, model reference robust fuzzy control, power system identification, power system stabilizer

INTRODUCTION

Large electric power systems are complex nonlinear systems and often exhibit low frequency electromechanical oscillations due to insufficient damping caused by adverse operating (Liu *et al*., 2005). These oscillations with small magnitude and low frequency often persist for long periods of time and in some cases they even present limitations on power transfer capability (Liu *et al*., 2005). In analyzing and controlling the power system's stability, two distinct types of system oscillations are recognized. One is associated with generators at a generating station swinging with respect to the rest of the power system. Such oscillations are referred to as "intra-area mode" oscillations. The second type is associated with swinging of many machines in an area of the system against machines in other areas. This is referred to as "inter-area mode" oscillations. Power System Stabilizers (PSS) are used to generate supplementary control signals for the excitation system in order to damp both types of oscillations (Liu *et al*., 2005). The widely used Conventional Power System Stabilizers (CPSS) are designed using the theory of phase compensation in the frequency domain and are introduced as a lead-lag compensator. The parameters of CPSS are determined based on the linearized model of the power system. Providing good damping over a wide operating range, the CPSS parameters should be fine tuned in response to both types of oscillations. Since power systems are highly nonlinear systems, with configurations and parameters which alter through time, the CPSS design based on the linearized model of the power system cannot guarantee its performance in a practical operating environment. Therefore, a robust PSS which considers the nonlinear nature of the plant and adapts to the changes in the environment is required for the power system (Liu *et al*., 2005). In order to improve the performance of CPSSs, numerous techniques have been proposed for designing them, such as intelligent optimization methods (Sumathi *et al*., 2007; Jiang and Yan, 2008; Sudha *et al*., 2009; Linda and Nair, 2010; Yassami *et al*., 2010), Fuzzy logic (Dubey, 2007; Hwanga *et al*., 2008) and many other techniques (Nambu and Ohsawa, 1996; Chatterjee *et al*., 2009). Also the application of robust control methods for designing PSS has been reported in (Bouhamida *et al*., 2005; Gupta *et al*., 2005; Mocwane and Folly, 2007; Sil

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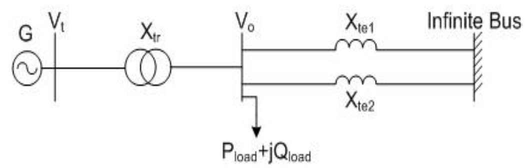

Fig. 1: A single machine infinite bus power system

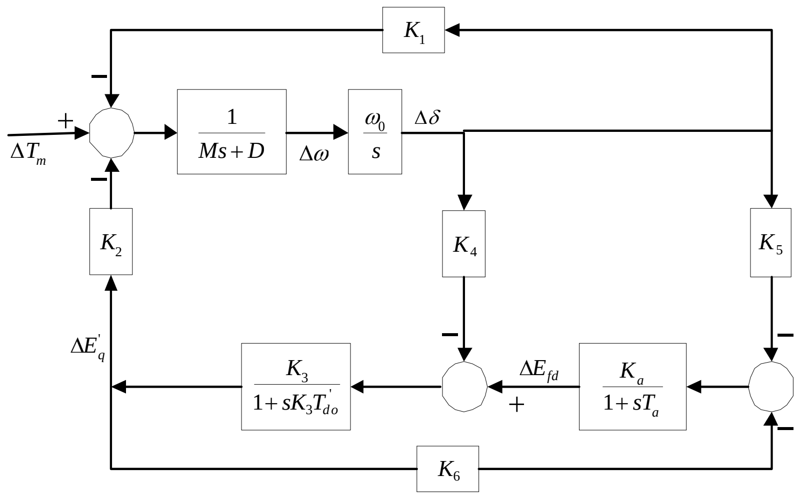

Fig. 2: Heffron-Phillips model of the power system

et al., 2009). This paper deals with a heuristic design method for the stability enhancement of a Single Machine Infinite Bus (SMIB) power system using Model Reference robust Fuzzy Control (MRRFC). In this new method, the procedure is as follows:

Step 1: Designing an optimal PID type PSS for the nominal operating condition using GA.
Step 2: Power system identification in the nominal condition and obtaining a model reference of power system with optimal PID-PSS.
Step 3: Calculation the error between model reference of power system and real power system with changing system operating conditions.
Step 4: Using the calculated error as input of a fuzzy controller to provide the damping signal.

The objective of this study is improvement of the operation of Power System Stabilizer (PSS). In order to reach this objective, in this paper a new robust Combination method based on Model Reference Adaptive Control (MRAC) and fuzzy logic control is proposed. To show effectiveness of the new MRRFC, this method is compared with the CPSS. Simulation results show that the proposed method guarantees robust performance under a wide range of operating conditions.

System under study: Figure 1 shows a single machine infinite bus power system (Yu, 1983). The static excitation system has been considered as model type *IEEE-ST1A*.

DYNAMIC MODEL OF THE SYSTEM

Non-Linear dynamic model: A non-linear dynamic model of the system is derived by disregarding the resistances and the transients of generator, transformers and transmission lines (Yu, 1983). The nonlinear dynamic model of the system is given as (1):

$$\begin{cases} \dot{\omega} = \dfrac{(P_m - P_e - D\Delta\omega)}{M} \\ \dot{\delta} = \omega_o(\omega - 1) \\ \dot{E}_q^{/} = \dfrac{(-E_q + E_{fd})}{T_{do}^{/}} \\ \dot{E}_{fd} = \dfrac{-E_{fd} + K_a(V_{ref} - V_t)}{T_a} \end{cases} \quad (1)$$

Linear dynamic model of the system: A linear dynamic model of the system is obtained by linearizing the non-linear dynamic model around the nominal operating condition. The linearized model of the system is obtained as (2) (Yu, 1983):

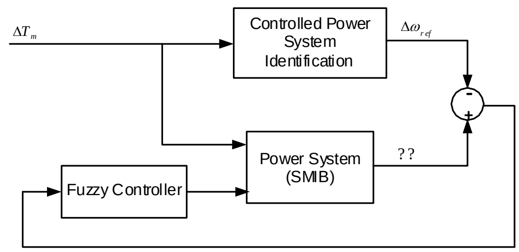

Fig. 3: The proposed method in detail

$$\begin{cases} \Delta \dot{\delta} = \omega_o \Delta \omega \\ \Delta \dot{\omega} = \dfrac{-\Delta P_e - D\Delta \omega}{M} \\ \Delta \dot{E}_q^{/} = (-\Delta E_q + \Delta E_{fd}) / T_{do}^{/} \\ \Delta \dot{E}_{fd} = -\left(1/T_a \right) \Delta E_{fd} - \left(K_a/T_a \right) \Delta V \end{cases} \qquad (2)$$

The block diagram model of the system is presented in Fig. 2. This model is known as Heffron-Phillips model (Yu, 1983). The model has some constants denoted by K_i. These constants are functions of the system parameters and the nominal operating condition. The nominal operating condition is given in the Appendix.

Dynamic model of the system in the state-space form: The dynamic model of the system in the state-space form is obtained as (3) (Yu, 1983):

$$\begin{bmatrix} \Delta \dot{\delta} \\ \Delta \dot{\omega} \\ \Delta \dot{E}_q^{/} \\ \Delta \dot{E}_{fd} \end{bmatrix} = \begin{bmatrix} 0 & \omega_0 & 0 & 0 \\ -\dfrac{K_1}{M} & 0 & -\dfrac{K_2}{M} & 0 \\ -\dfrac{K_4}{T_{do}^{/}} & 0 & -\dfrac{K_3}{T_{do}^{/}} & \dfrac{1}{T_{do}^{/}} \\ -\dfrac{K_A K_5}{T_A} & 0 & -\dfrac{K_A K_6}{T_A} & -\dfrac{1}{T_A} \end{bmatrix} \times \begin{bmatrix} \Delta \delta \\ \Delta \omega \\ \Delta E_q^{/} \\ \Delta E_{fd} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ \dfrac{1}{M} & 0 \\ 0 & 0 \\ 0 & \dfrac{K_A}{T_A} \end{bmatrix} \times \begin{bmatrix} \Delta T_m \\ \Delta V_{ref} \end{bmatrix} \qquad (3)$$

Analysis: In the nominal operating condition, the eigen values of the system are obtained using analysis of the state-space model of the system presented in (3) and these eigen values are shown in Table 1. It is clearly seen that the system has two unstable poles at the right half plane

Table 1: The eigen values of the closed loop system

-4.2797, -46.366, +0.1009 + j4.758, +0.1009 - j4.758

and therefore the system is unstable and needs the Power System Stabilizer (PSS) for stability.

Power system stabilizer: A Power System Stabilizer (PSS) is provided to improve the damping of power system oscillations. Power system stabilizer provides an electrical damping torque (ΔT_m) in phase with the speed deviation ($\Delta\omega$) in order to improve damping of power system oscillations (Yu, 1983). As referred before, many different methods have been applied to design power system stabilizers so far. In this paper a new Model Reference Robust Fuzzy Control (MRRFC) is considered to design PSS. In the next section, the proposed method is briefly introduced.

The proposed method: As mentioned before, in this paper a new Model Reference Robust Fuzzy Control (MRRFC) is considered to design PSS. Figure 3 shows the proposed method in detail. In this method, at first a PID type PSS designed using Genetic Algorithm (GA) and then this PID-PSS is applied to control of the nominal power system. This system with PID-PSS is called controlled power system that is shown in Fig. 4. After designing PID-PSS, system identification toolbox of the MATLAB software is used to identification of controlled power system. Then the identification result is used as the model reference of the power system. It is important to know that the model reference is presented as the controlled power system identification block in Fig. 3. With changing system operating condition, the error between identified model and real model is calculated and fed to a fuzzy controller. The output of fuzzy controller is fed to excitation system of generator as a stabilizer signal. In the next subsections the step by step stages of design process is developed.

PID-PSS design: In this section the PID-PSS parameters tuning based on the Genetic Algorithms is presented. The PID-PSS configuration is as (4):

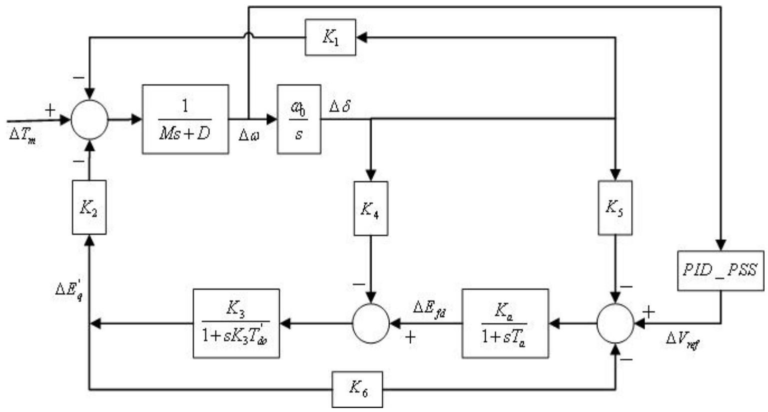

Fig. 4: Controlled power system

Table 2: Obtained parameters of PID-PSS using Genetic Algorithms

PID parameters	K_P	K_I	K_D
Obtained value	63.39	69.9974	11.9952

$$PID - PSS = K_P + \frac{K_1}{S} + K_D S \quad (4)$$

As it is presented in Fig. 4, the parameter ΔV_{ref} is modulated to output of PID-PSS and speed deviation Dw is considered as input to PID-PSS. The optimum values of K_P, K_I and K_D which minimize an array of different performance indexes are accurately computed using a Genetic Algorithms. In this study the performance index is considered as (5). In fact, the performance index is the Integral of the Time multiplied Absolute value of the Error (*ITAE*).

$$ITAE = \int_0^t t|\Delta\omega|dt \quad (5)$$

The parameter "t" in performance index is the simulation time. It is clear to understand that the controller with lower performance index is better than the other controllers. To compute the optimum parameter values, a 0.1 step change in reference mechanical torque (DTm) is assumed and the performance index is minimized using Genetic Algorithms. The following Genetic Algorithm parameters have been used in present research (Hemmati *et al*., 2010).

- Number of Chromosomes: 3 Population size: 48
- Crossover rate: 0.5 Mutation rate: 0.1

The optimum values of the parameters K_P, K_I and K_D are obtained using Hybrid Genetic Algorithms and summarized in the Table 2 (Hemmati *et al*., 2010).

Table 3: Parameters of the controlled power system model reference in nominal condition

Parameters	K	α	T_Z	T_{P1}	T_{p2}
Obtained value	1.1018×10^{-6}	0.6808	3.7386×10^{3}	0.1864	0.0032

Power system identification: System identification is an iterative process, where models are identified with different structures from data and compare model performance. Ultimately, the simplest model which best describes the dynamics of the system is chosen.

System identification is especially useful for modeling systems which cannot be easily represented in terms of first principles or known physical laws. The parameters of a black box model might not have a physical interpretation. Black-box models can be linear or nonlinear (Math works, MATLAB software, 2010). Therefore in this paper, system identification is used to identify power system model installed with PID-PSS. System Identification Toolbox of MATLAB is used to identify power system model, where the measured data determines the model structure (Math works, MATLAB software, 2010).

The transfer function of power system from T_m to ω is identified and the obtained transfer function is as (6):

$$G(s) = K\frac{1+T_Z s}{(1+2aT_{P1}s+(T_{P1}s)^2)(1+T_{P2}s)} \quad (6)$$

The parameters of obtained transfer function are listed in Table 3. The obtained model is used as model reference of power system for designing fuzzy PSS.

Fuzzy controller design: In order to providing stabilizer signal, the output of obtained model reference of power system is compared with output of real power system and

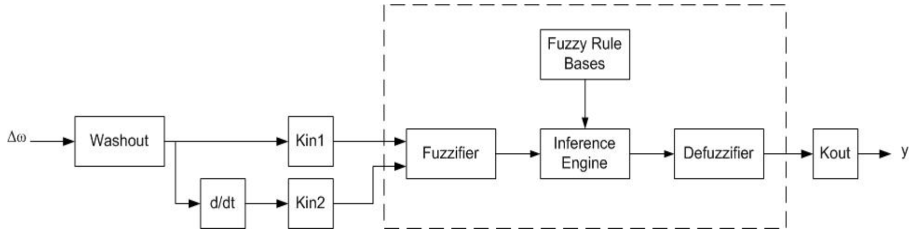

Fig. 5: Fuzzy controller

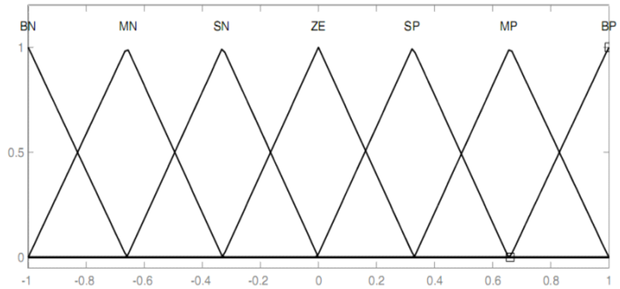

Fig. 6: Membership function of inputs and output

Table 4: The linguistic variables for inputs and output

Big Positive (BP)	Medium Positive (MP)	Small Positive (SP)
Big Negative (BN)	Medium Negative (MN)	SmallNegative (SN)
Zero (ZE)		

the error signal is fed to a fuzzy controller. The Fuzzy controller provides stabilizer signal in order to damping power system oscillations. Here the proposed Fuzzy controller block diagram is given in Fig. 5. In fact, it is a nonlinear lead-lag Fuzzy logic controller with two inputs and one output. The inputs are filtered by washout block to eliminate the DC components (Hemmati *et al*., 2010). Also there are three parameters denoted by K_{in1}, K_{in2} and K_{out} which are defined over an uncertain range and then obtained by Genetic Algorithms optimization method. Therefore the boundaries of inputs and output signals are tuned on an optimal value (Hemmati *et al*., 2010).

Fuzzy controller parameters: In this study the membership function for input variables and output variable of fuzzy controller are considered as Table 4.

Also "triangular membership functions" are used as membership functions for the input and output variables. The Fig. 6 shows this in detail indicating the range of the variable. The Fuzzy rules which are used in this paper are listed in Table 5. The Defuzzification method followed in this study is the "Center of Area Method" or "Gravity method" (Hemmati *et al*., 2010).

Table 5: Fuzzy rule bases

	Error						
d(Error)/dt	BN	MN	SN	ZE	SP	MP	BP
BN	BN	BN	BN	BN	MN	SN	ZE
MN	BN	MN	MN	MN	SN	ZE	SP
SN	BN	MN	SN	SN	ZE	SP	SP
ZE	MN	MN	SN	ZE	SP	MP	MP
SP	SN	SN	ZE	SP	SP	MP	BP
MP	SN	ZE	SP	MP	MP	MP	BP
BP	ZE	SP	MP	BP	BP	BP	BP

Fuzzy controller tuning using genetic algorithms: In this section the membership functions of the proposed fuzzy block are tuned by K parameters (K_{in1}, K_{in2} and K_{out}). These K parameters are obtained based on Genetic Algorithms optimization method. The optimum values of K_{in1}, K_{in2} and K_{out} which minimize an array of different performance indexes are accurately computed using Genetic Algorithms. In this study the ITAE is considered as performance index in (Hemmati *et al*., 2010).

In order to compute the optimum parameter values, a 0.1 step change in reference mechanical torque (DTm) is assumed and the performance index is minimized using Genetic Algorithms. The following Genetic Algorithm parameters have been used in present research (Hemmati *et al*., 2010).

- Number of Chromosomes: 3 Population size: 48
- Crossover rate: 0.5 Mutation rate: 0.1

The optimum values of the parameters K_{in1}, K_{in2} and K_{out} are obtained using genetic algorithms and summarized in the Table 6.

Table 6: Obtained parameters K_{in1}, K_{in2} and K_{out} using Genetic Algorithms

Parameters	K_{in1}	K_{in2}	K_{out}
Obtained value	909.3946	453.5364	0.4435

Table 7: The calculated ITAE

	MRRFC-PSS	CPSS
Nominal operating condition	5.0672×10^{-4}	5.5686×10^{-4}
Heavy operating condition	5.2480×10^{-4}	7.2451×10^{-4}
Very heavy operating condition	5.2534×10^{-4}	8.9021×10^{-4}

SIMULATION RESULTS

The proposed MRRFC is evaluated on the test system given in section 2 (single machine infinite bus power system). In order to comparison purposes, a classical lead-lag PSS based on phase compensation technique (CPSS) is carried out on the test system. The phase compensation technique is a well known approach to design classical type PSSs (Yu, 1983). The proposed CPSS is provided as (7). Also a washout block with time constant 10 sec is incorporated for the proposed CPSS.

$$CPSS = \frac{35(0.3S+1)}{(0.1S+1)} \tag{7}$$

In the PSS design, an important subject is to evaluate the designed PSS under power system condition changing. The robustness of PSS should be evaluated under different loading conditions and system operating conditions. In this scope, the following conditions are considered to assessment of the proposed PSS under different loading conditions:

- Nominal operating condition
- Heavy operating condition (20% changing parameters from their typical values)
- Very heavy operating condition (50% changing parameters from their typical values)

One the most important benchmarks to evaluate the performance of PSS is ITAE index. The proposed index is calculated for the proposed method and also CPSS. To calculation of ITAE, a 10% step change in the reference mechanical torque is incorporated and the ITAE is calculated at all operating conditions (Nominal, heavy and very heavy) and results are listed in Table 7. The proposed Table clearly shows the effectiveness of the proposed method in comparison with CPSS. MRRFC results lower ITAE at all operating condition rather than CPSS. In fact, MRRFC mitigates oscillations better than CPSS. The stability of power system is improved by MRRFC. The effect of MRRFC on the power system stability is clearer in heavy loading conditions. For more details, the power system responses under different conditions are shown in Fig. 7. The figure shows the ability of MRRFC in power system stability enhancement via damping oscillations. At all conditions from nominal to heavy, the MRRFC has a greater performance. The proposed method has an effective performance in power system stability enhancement. With changing system condition from nominal to heavy and very heavy, the MRRFC shows a robust and permanent response. But CPSS performance becomes poor and poorer in heavy and very heavy conditions respectively. Under heavy condition, the CPSS not able to provide sufficient damping torque and system goes to fluctuate. But in the

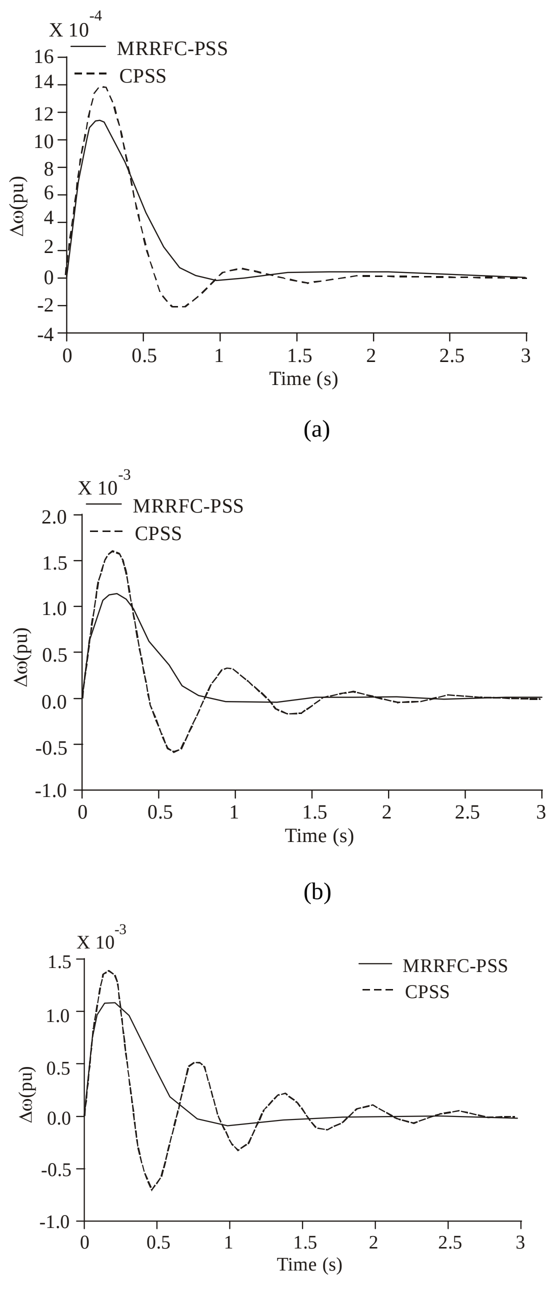

Fig. 7: Dynamic responses Δω following 0.1 step in the reference mechanical torque ΔTm, (a) Nominal operating condition, (b) Heavy operating condition, (c) Very heavy operating condition

Table 8: The nominal system parameters

Generator	M = 10 Mj/MVA	T'_{do} = 7.5 s	X_d = 1.68 p.u.
	X_q = 1.6 p.u.	$X'd$ = 0.3 p.u.	D = 0
Excitation system		K_a = 50	T_a = 0.02 s
Transformer		X_{tr} = 0.1 p.u.	
Transmission line	X^t_{el} = 0.5 p.u.	X_{te2} = 0.5 p.u.	
Operating condition	V_t = 1.05 p.u.	P = 1 p.u.	Q = 0.2 p.u.

proposed method, the injected stabilizing signal can controls power system oscillations.

CONCLUSION

In this study a new heuristic mixed method has been carried out to PSS design. In the proposed method, a Model Reference Robust Fuzzy Control (MRRFC) scheme incorporated to PSS design under. In the proposed method, the difference between reference model and output is sent to a fuzzy controller to provide stabilizing signal. This structure provides to advantages. In first the injected stabilizing signal is harmonize with error between reference and output. Second, the inner feedback loop increases power system stability margin. Also the proposed fuzzy block guarantees power system responses with changing conditions. The proposed method was carried out on a typical Single Machine Infinite Bus (SMIB) power system. The robustness of the proposed method tested under different loading condition from nominal to heavy. Results of nonlinear simulation clearly showed the viability and robustness of the proposed MRRFC. The MRRFC lumps the characteristics of fuzzy, adaptive and robust controllers in a one block. This innovation helps to control of system in a better way.

Appendix: The nominal parameters and operating conditions of the system are listed in Table 8.

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