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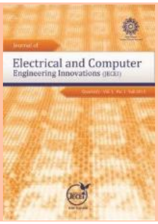

Alleviating the Small-Signal Oscillations of the SMIB Power System with the TLBO–FPSS and SSSC Robust Controller

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ABSTRACT

Power systems are subjected to small–signal oscillations that can be caused by sudden change in the value of large loads. To avoid the dangers of these oscillations, the Power System Stabilizers (PSSs) are used. When the PSSs can not be effective enough, installation of the Thyristor–based compensators to increase the oscillations damping is a suitable method. In this paper, a Static Synchronous Series Compensator (SSSC) is used in Single–Machine Infinite–Bus (SMIB). To control the signal of the output voltage of SSSC, a robust controller is used. Also, we proposed a hybrid control method to adjust the PSS voltage using Teaching–Learning Based Optimization (TLBO) algorithm and Fuzzy Inference System (FIS). Objective functions of designing parameters are based on Integral of Time multiplied by Absolute value of the Error (ITAE). The time–variations of angular speed deviations are investigated in different modes, including: with SSSC/PSS, without SSSC/PSS, different input mechanical power, and different system parameters.

1. INTRODUCTION

Modern power systems are designed to operate efficiently to supply power on demand to various load centers with high reliability [1]. The generation stations are often located at distant locations for economic, environmental and safety reasons [1]. Today, advanced Flexible AC Transmission System (FACTS) devices, due to fast operation [2], are used for optimal control and transmission of electrical energy. One of the most commonly used equipment in the transmission system is the Static Synchronous Series Compensator (SSSC). This device employs power electronic converters [3]. With the capability to change its reactance characteristic from capacitive to inductive, the SSSC is very effective in controlling power flow in the power system [4].

Heretofore, various researches have been conducted on the analysis, control, and optimization of SSSC performance in the power systems. In [5], five mathematical models of the SSSC suitable for three-phase analysis, using Newton Power Flow (NPF) algorithm, are proposed. A novel control strategy for an SSSC dedicated to sub-synchronous resonance (SSR) mitigation using eliminate the frequency components of the line current corresponding to the natural resonance frequencies of the generator shaft is introduced in [6]. Reference [7] proposes a similar control strategy, but using hybrid compensation with SSSC based on three-level 24-pulse voltage source converter (VSC) is presented to increase the power transfer capability. The Kalman-Filter (KF) for state estimation of sub-synchronous components present in series compensated line and the mitigation of SSR is proposed in [8]. By using a new scheme for the control signal of SSSC, in two areas, SSSC becomes able to compensate for load changes in both areas on both sides of SSSC [2].

The linearized model of the damping control function of SSSC integrated into power systems is established, and methods to design controller are proposed for both cases of Single-Machine Infinite-Bus (SMIB) and Multi-Machine Power Systems (MMIB) in

[9]. For the improvement of transient stability, a novel Adaptive Neuro-Fuzzy Inference System (ANFIS) method can have quick response, and greatly improve the voltage profile of the system under severe disturbances [10]. A novel method is developed in [11] for designing the output feedback controller for SSSC. Then, this controller function is solved by particle swarm optimization (PSO) algorithm and evaluated for SMIB and MMIB power systems.

With growing transmission line loading, the Power System Stabilizer (PSS) may not provide enough damping for the inter-area power oscillations in a complex power system [12]. Many methods have been proposed to design the PSS [13–15]. These methods do not consider the occurrence of system parameters and loading uncertainties in the power system modelling; so, the efficacy of FACTS devices against system uncertainties cannot be guaranteed [12]. Reference [12] proposed hybrid control schemes, consisted of Particle Swarm Optimization (PSO) algorithm optimized FIS controller parameters for PSS, and H_∞ robust controller for TCSC, for compensation of parametric and non-parametric uncertainties arising in modern power systems. Based on the simulation results, the robustness and superiority of the proposed control are proved. In [16], a Genetic Algorithm–based Fuzzy (GAF) controller is proposed to design PSS that synthesize the advantage of the GAs and fuzzy control techniques to achieve adaptable robust performance.

In this paper, an SMIB power system with the installed PSS is considered. For PSS control, FIS parameters are optimized by TLBO algorithm. To control the SSSC, a new reduced–order robust (H_∞) controller is used from [12]. To prove fitness and effectiveness of proposed method, an SMIB power system is considered and simulation results will be presented in different modes. The paper is structured as follows: In Section 2, Heffron-Phillips (H–F) model of an SMIB with SSSC and PSS is described. Section 3 investigates the FIS controller for PSS, and proposes the optimization method using TLBO algorithm. In Section 4, robust control function to optimize the SSSC signal value is presented based on [12]. In Section 5, computer simulations are presented. Section 6 is the conclusion of paper.

2. THE HEFFRON–PHILLIPS MODEL

Basic schematic of an SMIB power system installed with a SSSC is shown in Figure 1 [4]. An SSSC consists of a series coupling transformer with a leakage reactance, x_{sct}, a VSC–based unit, and a DC capacitor [4, 11]. By controlling the modulation ratio, m, and modulation phase, ϕ, the SSSC voltage, V_{SSSC}, can be regulated. The H–F model of a SMIB with installed SSSC is shown in Figure 2. In this model, unlike TCSC [12], there are five variables. The capacitor voltage, V_{dc}, is an auxiliary variable in this model for controlling the V_{SSSC}. The state-space model of Figure 2 is given by:

$$\dot{\mathbf{X}} = \mathbf{AX} + \mathbf{BU} \tag{1}$$

where, **X** is the state vector, **U** is the control vector, and **A** and **B** are the state and input matrices, respectively, and defined as follows:

$$\mathbf{A} = \begin{bmatrix} 0 & \omega_0 & 0 & 0 & 0 \\ \frac{-K_1}{M} & \frac{-D}{M} & \frac{-K_2}{M} & 0 & \frac{-K_{pdc}}{M} \\ \frac{-K_4}{T'_{d0}} & 0 & \frac{-K_3}{T'_{d0}} & \frac{-1}{T'_{d0}} & \frac{-K_{qdc}}{T'_{d0}} \\ \frac{-K_A K_5}{T_A} & 0 & \frac{-K_A K_6}{T_A} & \frac{-1}{T_A} & \frac{-K_A K_{vdc}}{T_A} \\ K_7 & 0 & K_8 & 0 & K_9 \end{bmatrix},$$

$$\mathbf{X} = \begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta E'_q \\ \Delta E_{fd} \\ \Delta V_{DC} \end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix} 0 & 0 \\ 0 & \frac{-K_{pm}}{M} \\ 0 & \frac{-K_{qm}}{M} \\ \frac{K_A}{T_A} & \frac{-K_A K_{vm}}{T_A} \\ 0 & K_{dm} \end{bmatrix}, \quad \mathbf{U} = \begin{bmatrix} \Delta u_{PSS} \\ \Delta m \end{bmatrix}$$

where, K_1, K_2, K_3, K_4, K_5, K_6, K_7, K_8, K_9, ω_0, D, M, T'_{d0}, T_A, K_A, K_{pm}, K_{vm}, K_{dm}, K_{pdc}, K_{qdc}, and K_{vdc} are the system parameters.

With controlling the signals of Δu_{pss} and Δm, the value of injection voltage by SSSC can be controlled. In this paper, the signal of Δu_{pss} is controlled by a proposed novel method by FIS, where the parameters of FIS are optimized by TLBO algorithm.

For controlling the signal of Δm, a robust control is used.

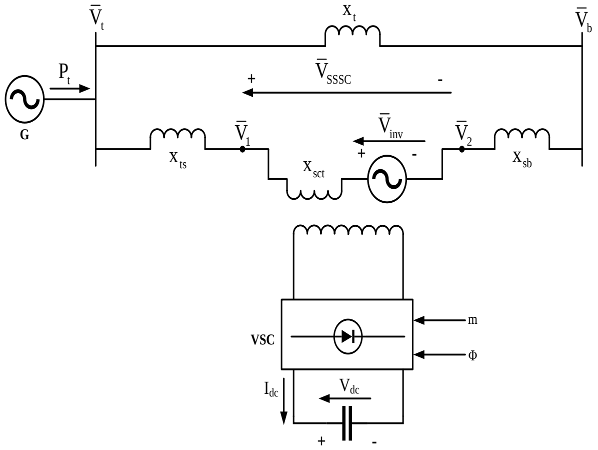


Figure 1: An SMIB power system with installed SSSC.

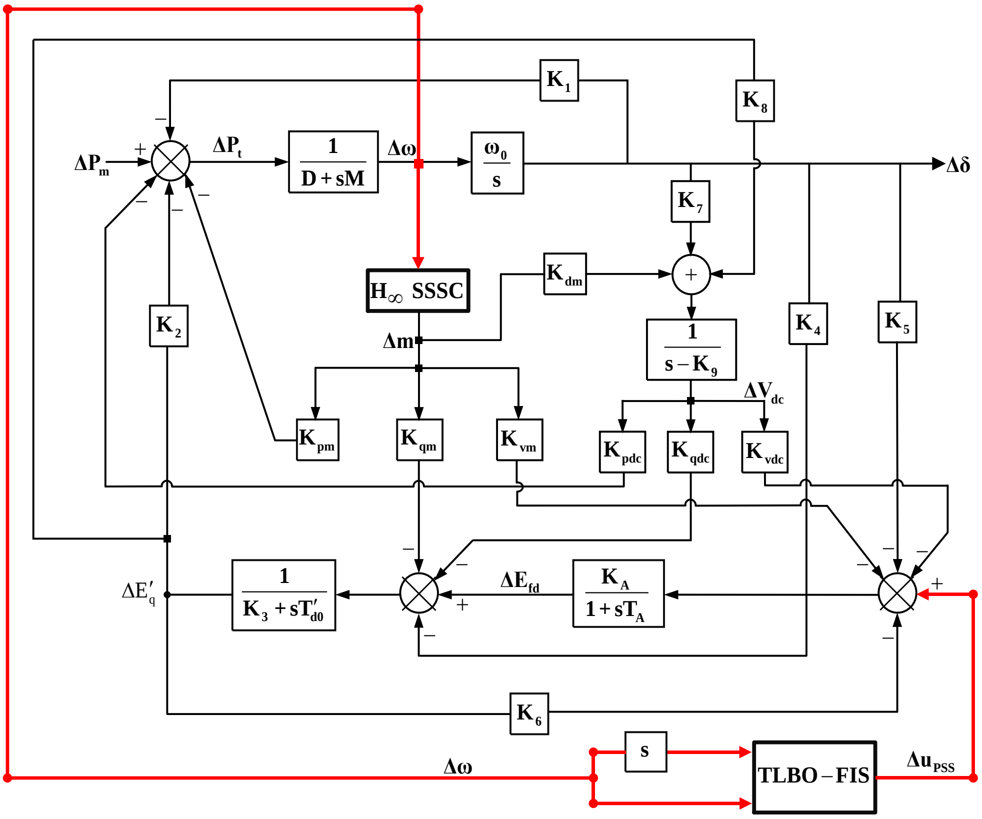


Figure 2: The H–F model of a SMIB with installed H∞ SSSC and TLBO–FIS controllers.

3. PSS CONTROLLER DESIGN BY TLBO–FIS

A. PSS Design by FIS

The Mamdani type of FIS is considered to control the PSS. To reach the maximum flexibility in output results of FIS, seven cases for inputs and output Membership Functions (MF) were chosen as shown in Figure 3. The linguistic labels of MFs are marked as in Figure 3, BN (Big Negative), MN (Medium Negative), SN (Small Negative), ZR (Zero), SP (Small Positive), MP (Medium Positive), BP (Big Positive) MFs are used to convert the fuzzy values between 0 and 1 for inputs and output value both [12] and defined in Table 1. The inputs are speed and acceleration (speed derivative), and the output is PSS voltage (Δu_{PSS}). There are 49 rules for defined MFs. The surface viewer of the MFs relation of the output variable on the input variables is shown in Figure 4. The structure of proposed FIS is shown in Figure 5.

TABLE 1
DEFINED OUTPUT VALUES IN FIS [12]

INPUT1 (Δω)	INPUT2 (d(Δω)/dt)						
	BN	MN	SN	ZR	SP	MP	BP
BN	BN	BN	BN	BN	MN	MN	SN
MN	BN	MN	MN	MN	SN	SN	ZR
SN	BN	MN	MN	MN	SN	SN	ZR
ZR	MN	SN	SN	ZR	SP	SP	MP
SP	SN	ZR	ZR	SP	SP	MP	MP
MP	ZR	SP	SP	MP	MP	MP	BP
BP	SP	MP	MP	BP	BP	BP	BP

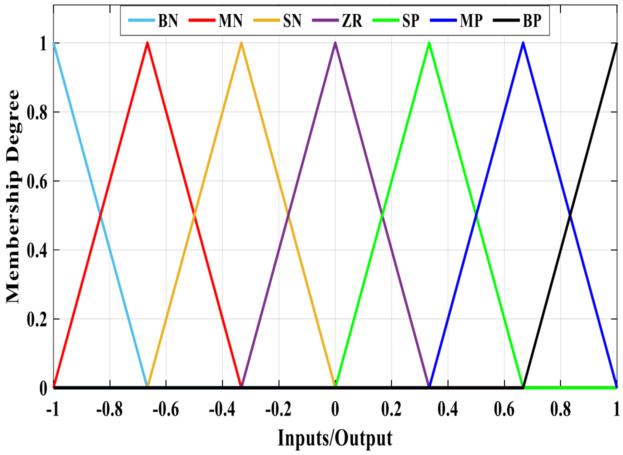


Figure 3: MFs of FPSS for input and output variables.

B. TLBO Algorithm

The TLBO algorithm is a teaching-learning process inspired algorithm proposed by Rao et al. [17–19] based on the effect of the influence of a teacher on the output of learners in a class. The process of TLBO is divided into two parts: the first part consists of the "Teacher Phase" and the second part consists of the "Learner Phase" [17]. The "Teacher phase" means learning from the teacher and the "Learner phase" means learning through the interaction between learners [20]. In this optimization algorithm, a group of learners constitutes the population [21], and different subjects offered to the learners are considered as different design variables of the optimization problem and a learner's result is analogous to the 'fitness' value of the optimization problem. Then, the best solution in the entire population is considered as the teacher. The design variables are actually the parameters involved in the objective function of the given optimization problem and the best solution is the best value of the objective function [20]. TLBO algorithm is a population-based algorithm which simulates the teaching-learning process of the class room. This algorithm requires only the common control parameters such as the population size and the number of generations and does not require any algorithm–specific control parameters [19]. Due to its simple concept and high efficiency, TLBO has become a very attractive optimization technique and has been successfully applied to many real world problems [17–21].

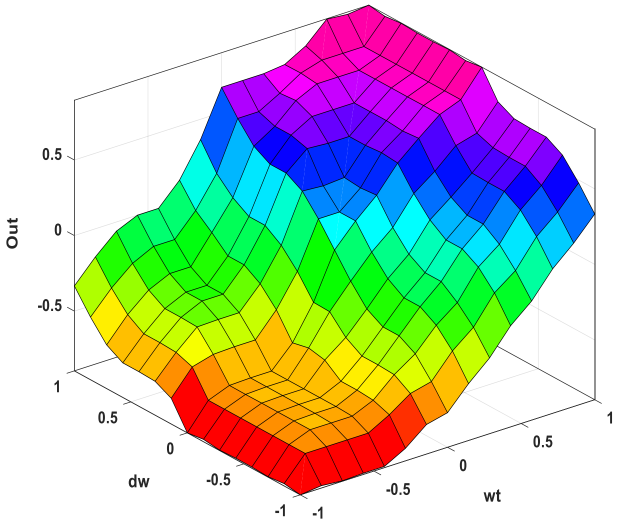


Figure 4: Surface viewer of the MFs.

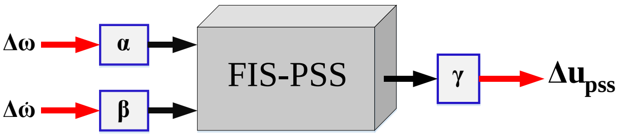


Figure 5: structure of proposed FIS–PSS.

C. Solving the PSS–FIS by TLBO Algorithm

The TLBO algorithm will be optimized the FIS parameters, α, β, and γ, as shown in Figure 5. The objective function is formulated as the minimization of the Integral of Time multiplied by the Absolute value of Error (ITAE), and the fitness function is described as [12, 16]:

$$\mathrm{MAX}\left\{\mathrm{Fitness}=\frac{1}{1+\mathrm{ITAE}}\right\} \tag{2}$$

where,

$$\mathrm{ITAE}=\int_0^t t.\left|\Delta\omega(t)\right|dt \tag{3}$$

The Flow–Chart of proposed control method for PSS is shown in Figure 6.

4. ROBUST SSSC CONTROLLER

In this paper, the controller of SSSC signal is based on H∞ robust control that is studied in [12]. To increase the time response and reduce the simulation time, the reduced–order robust SSSC controller is considered, which is formulated as:

$$K_S=K_\infty=\frac{374S^2+492\,S+7566}{S^3\;+8.5\,S^2+185\,S+1} \tag{4}$$

The reason of using of reduced order of SSSC controller is presented in Figure 7. In this figure, the Bode–plot of two transfer functions, i.e. six–order from [12] and three–order from (4), are illustrated. With a good approximation, the performance of both transfer function is similar. This reduction in order helps to increase the controller speed.

Also, according to [12], a PI controller can be added to this system, which is described as follows:

$$W_1=\frac{S+1}{0.9\,S}=\frac{10}{9}\left(1+\frac{1}{S}\right) \tag{5}$$

5. SIMULATION RESULTS

An SMIB power system with installed SSSC is considered to assess the effectiveness of offered method. The input of system is random mechanical power of generator (ΔP_m) that is shown in Figure 8. Simulation is done in MATLAB/R2016b, and a 64bit–Core i7–12 GB RAM computer system. To prove the robustness of the TLBO algorithm, its results are compared with other modes. Also, with changing the system parameters, the results are investigated.

The initial value of parameters of algorithm, power system and controllers, for optimization, are given in Appendix A. After simulation, the FIS–PSS parameters are optimized, and the Final values, are α = 9.9855, β = 0.0707, and γ = 4.9889. Figure 9 shows the ITAE values for all iterations of algorithm, and the final value is 0.0000447 that is acceptable. In Figure 10, the dynamic time responses of rotor angular speed deviation (Δω) are shown in different sets of presence/absence of H∞ SSSC and TLBO–FIS controllers.

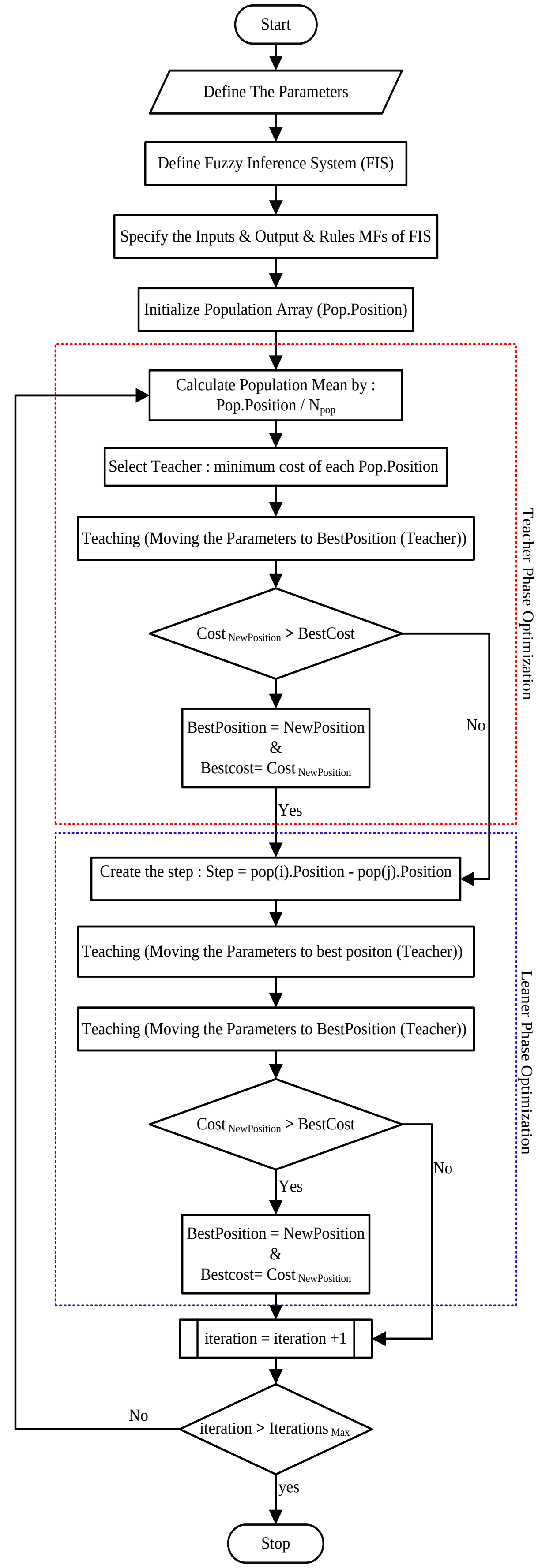


Figure 6: The Flow–Chart of proposed control method.

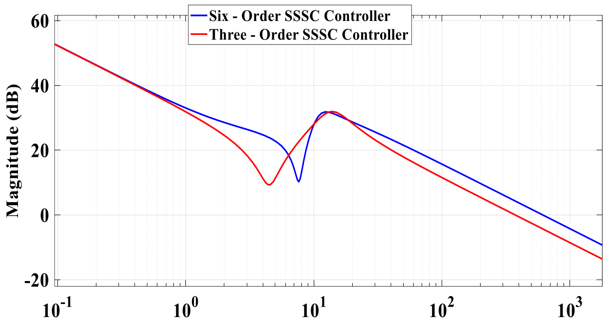


Figure 7: Bode–Plot of six–order and three–order controller functions.

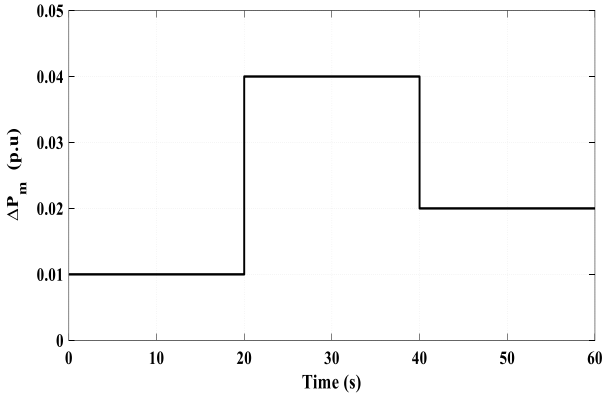


Figure 8: Input mechanical power of generator.

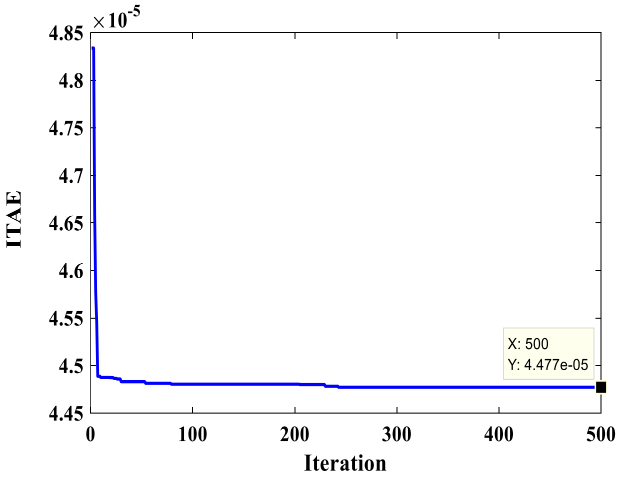


Figure 9: ITAE values for TLBO algorithms.

The damping–time of system response in D = 7 is more than D = 8 (see Figure 11–b). On the other hand, when D ≥ 8, the damping–time decreases (see Figure 11–c and Figure 11–d). However, in the all cases, the results of simulation with TLBO–FPSS and H_∞ SSSC controllers were best. The initial value of M is considered to M = 8. If the amount of M increases, the system response will be different. With M = 10, damping–time will increase when there is no SSSC and PSS (see Figure 12–a). If M = 12, the system will be

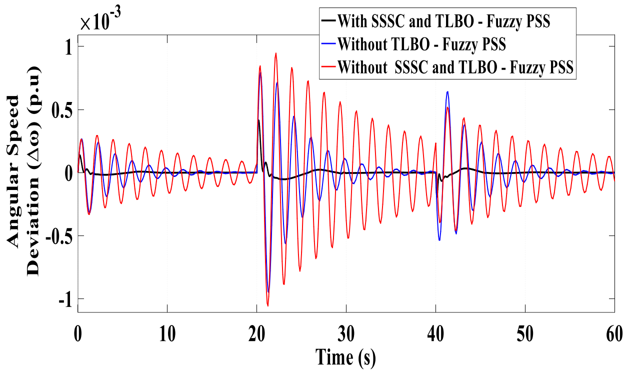
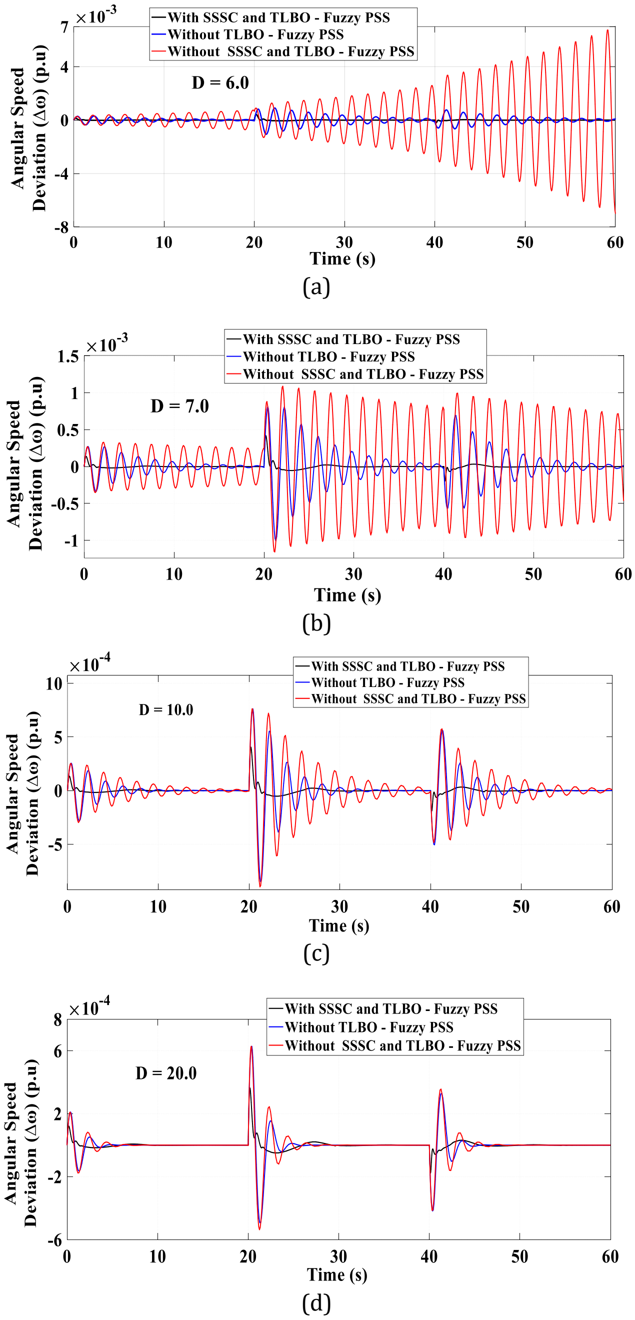


Figure 10: Angular speed deviation (Δω) with/without H∞ SSSC and TLBO–FPSS.



(a)

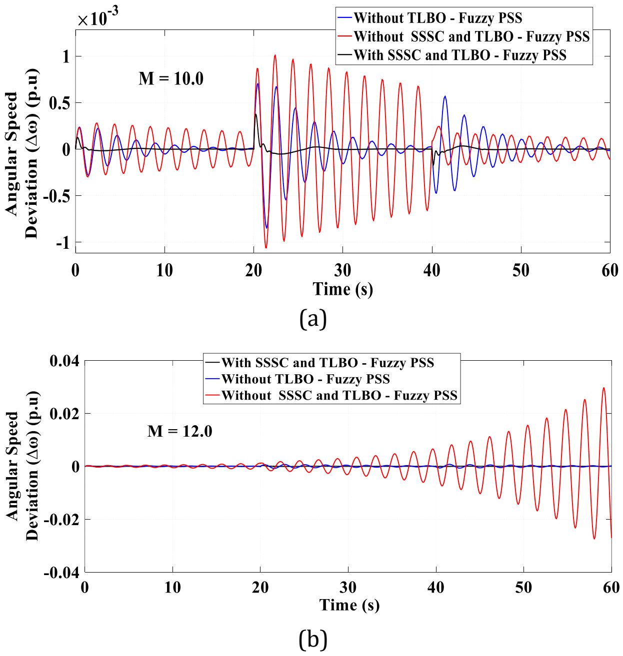
(b)

(c)

(d)

Figure 11: Angular speed deviation (Δω) with/without H∞ SSSC and TLBO–FPSS with different values of D.

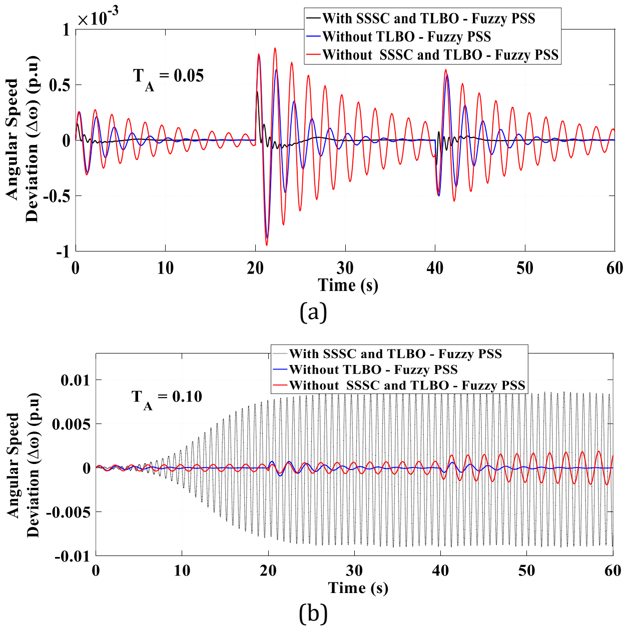
unstable without SSSC and PSS, but there are no changes in response with SSSC/PSS (see Figure 12–b). The time–constant of AVR (T_A) is very effective in response of system with/without SSSC and PSS. If T_A increases, Δω will go to instability. Likewise, when its value is much larger than initial value (see Figure 13–b), Δω has irreversible instability with/ without SSSC and TLBO–FPSS.



(a)

(b)

Figure 12: Angular speed deviation (Δω) with/without H∞ SSSC and TLBO–FPSS with different values of M (D = 10).



(a)

(b)

Figure 13: Angular speed de viation (Δω) with/without H∞ SSSC and TLBO–FPSS with different values of T_A (D = 10).

The quantitative comparisons of domain magnitude at start and end of every operation point, for all cases are carried out in Table 2.

TABLE 2
ROTOR ANGULAR SPEED DEVIATION (Δω) IN DIFFERENT MODES

Mode		$\Delta P_m = 0.01$ $(0 \le t \le 20)$						$\Delta P_m = 0.04$ $(20 \le t \le 40)$						$\Delta P_m = 0.02$ $(40 \le t \le 60)$					
		Start (t = 0)			End (t = 20)			Start (t = 20)			End (t = 40)			Start (t = 40)			End (t = 60)		
		X	*Y*	*Z*	*X*	*Y*	*Z*	*X*	*Y*	*Z*	*X*	*Y*	*Z*	*X*	*Y*	*Z*	*X*	*Y*	*Z*
Main parameters (Fig. 9)		1.4	2.6	2.6	0	0	0.7	4.1	7.9	8.4	0	0.1	2.3	-1.9	-5.3	-3.9	0	0	1.2
D = 6 (Fig. 10–a)		1.4	2.8	2.7	0	0	7.5	4.3	9.2	8.3	0	-1.1	26	-1.9	-6.0	-31	0	0.9	67
D = 7 (Fig. 10–b)		1.4	2.7	2.7	0	0	2.4	4.2	8.1	8.7	0	-0.2	8.1	-1.9	-5.6	-9.1	0	0.14	7.6
D = 10 (Fig. 10–c)		1.3	2.6	2.5	0	0	-0.1	4.0	7.6	7.6	0	0	-0.2	-1.9	-5.1	-4.8	0	0	0.5
D = 20 (Fig. 10–d)		1.2	2.0	2.1	0	0	0	3.6	6.3	6.3	0	0	0	-1.8	-4.2	-4.1	0	0	0
D = 10	*M = 10 (Fig. 11–a)*	1.2	2.4	2.3	0	0.1	-1.8	3.7	7.0	8.6	0	2.5	-6.6	-1.7	-4.7	2.4	0	-0.1	-1.1
	M = 12 (Fig. 11–b)	1.2	2.2	2.1	0	-0.6	11	3.5	6	14	0	-1.8	65	-1.6	-6.1	-73	0	1.8	296
	T_A = 0.05 (Fig. 11–b)	1.4	2.5	2.5	0	0	-0.5	4.3	7.6	7.8	0	0	-1.5	-2.2	-5.0	-4.9	0	0	1.0
	T_A = 0.10 (Fig. 11–b)	1.5	2.5	2.6	77	0	-3.1	-78	7.0	4.0	-90	0	-4.0	92	-5	-12	83	0.2	14.3

X: with SSSC and TLBO–FPSS Y: with SSSC and without TLBO–FPSS Z : without SSSC and TLBO–FPSS

6. CONCLUSION

In this paper, a hybrid control method is proposed for controlling the SMIB power system with installed SSSC and PSS. Using TLBO algorithm, a controller is designed for control and adjustment of the PSS voltage. For controlling the SSSC signal, a reduced–order H_∞ robust controller is used, which controls the DC voltage of capacitor.

The FPSS controller parameters were optimized by TLBO algorithm. In this optimization, the objective function was considered as minimization of angular speed errors, that has remarkable results. The results show that the proposed method, H_∞ SSSC with TLBO–FPSS, has better effect on damping of the angular speed in comparing of without SSSC or TLBO–FPSS. Also, for proving the robustness of proposed method, the system parameters are changed. In all modes, damping of Δω with paper proposed method is effective.

APPENDIX A

$K_1 = 0.333$, $K_2 = 0.6702$, $K_3 = 2.00$, $K_4 = 0.1845$, $K_5 = -0.29$, $K_6 = 0.5483$, $K_7 = -1.9772$, $K_8 = 0.4067$, $K_9 = -0.0786$, $\omega_0 = 377$, $D = 8$, $M = 8$, $T'_{d0} = 5.044$, $T_A = 0.01$, $K_A = 100$, $K_{pm} = 0.5355$, $K_{vm} = 0.8882$, $K_{qm} = -1.813$, $K_{dm} = -0.2212$ $K_{pdc} = 0.1805$, $K_{qdc} = -0.6112$, $K_{vdc} = 0.2994$

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