Comparative Performance Analysis of Particle Swarm Optimization and Interval Type-2 Fuzzy Logic-Based TCSC Controller Design

Manoj Kumar Panda, G. N. Pillai and Vijay Kumar

Abstract In this paper, an interval type-2 fuzzy logic controller (IT2FLC) is proposed for thyristor-controlled series capacitor (TCSC) to improve power system damping. It has been tested on the single-machine infinite-bus (SMIB) system. The proposed controller performance is compared with particle swarm optimization (PSO) and type-1 fuzzy logic controller (T1FLC)-based TCSC. In this problem, the PSO algorithm is applied to find out the optimal values of parameters of lead-lag compensator-based TCSC controller. The comparative performance is analyzed based on the simulation results obtained for rotor speed deviation and power angle deviation plot, and it has been found that for damping oscillations of SMIB system, the proposed IT2FLC is quite effective. The proposed controller is also robust subjected to different operating conditions and parameter variation of the power system.

Keywords Particle swarm optimization · Type-2 fuzzy system · TCSC · Fuzzy logic controller

1 Introduction

The particle swarm optimization (PSO) algorithm is a population-based, stochastic and multi-agent parallel global search technique [1]. The PSO algorithm is based on the mathematical modeling of various collective behaviors of the living creatures that

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display complex social behaviors. In the PSO algorithm, while a particle is developing a new situation, both the cognitive component of the relative particle and the social component generated by the swarms are used. This situation enables the PSO algorithm to effectively develop the local situations into global optimum solutions [2]. PSO is a computational intelligence-based technique that is not largely affected by the size and nonlinearity of the problem and can converge to the optimal solution in many problems where most analytical methods fail to converge. It can therefore be effectively applied to different optimization problems in power systems [1]. The PSO is successfully applied in almost all areas of power system engineering like reactive power and voltage control, economic dispatch, power system reliability and security [1]. Very few applications of type-2 fuzzy logic to power system problems were reported in literature [3–6].

Thyristor-controlled series capacitor (TCSC) is one of the important members of flexible AC transmission systems (FACTS) family for damping the power oscillations also to enhance the transient stability [7, 8]. Over the years, artificial intelligence techniques [9–11] being used in developing TCSC models.

In this paper, a comparison has been made between the performance of three types of TCSC controller, i.e., PSO optimized lead lag compensator based TCSC (PSOLLC) in which the time constants and gain of LLC are optimized, a fuzzy logic control (FLC)-based TCSC controller, and the proposed IT2FL-based TCSC controller. Simulation is carried out for single-machine infinite-bus (SMIB) system. The effectiveness of the proposed controller is also tested at all loading conditions with transmission line reactance variation.

Section 2 of this paper describes about basic theory of PSO and its application in TCSC controller design. Type-2 fuzzy logic controller (IT2FLC)-based TCSC is presented in Sect. 3. Results are given and discussed in Sect. 4 and finally conclusion is presented in Sect. 5.

2 Particle Swarm Optimized Lead-Lag Compensator-based TCSC

In this paper, the PSO technique is applied to find out the optimal values of TCSC controller gain K_T and time constants T_{1T} and T_{3T} as shown in Fig. 1.

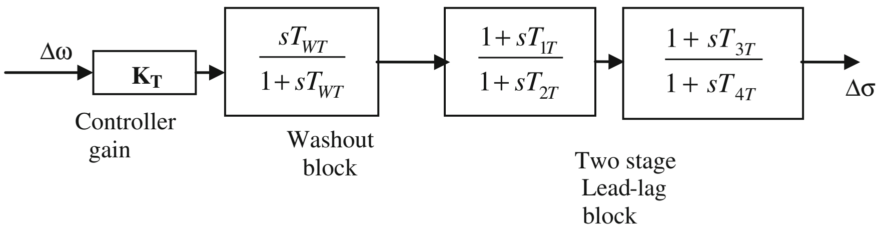

Fig. 1 TCSC controller block diagram

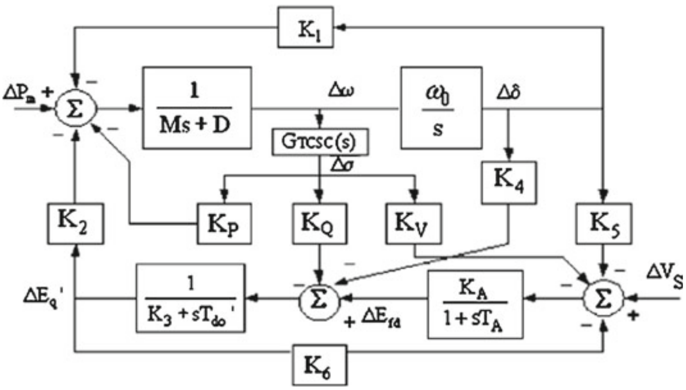

Fig. 2 Modified Phillips–Heffron model of SMIB system using TCSC [12]

2.1 TCSC Controller Description

The TCSC controller consists of a gain block having gain K_T, a washout block, which is a high-pass filter to allow signals associated with oscillations in input signal to pass unchanged and a two-stage phase-compensation block to compensate for the phase lag between the input and output signal.

The transfer function of the TCSC controller is

$$y = K_T \left(\frac{sT_{wT}}{1 + sT_{wT}} \right) \left(\frac{1 + sT_{1T}}{1 + sT_{2T}} \right) \left(\frac{1 + sT_{3T}}{1 + sT_{4T}} \right) x \tag{1}$$

where y is the output signal and x is the input signal of the TCSC controller, respectively. The TCSC controller is connected in the SMIB system model as shown in the Fig. 2. The objective of the TCSC controller is to minimize the power system oscillations after a disturbance to improve the stability by contributing a damping torque [10].

2.2 Application of PSO for Computing Optimum TCSC Controller Parameter

The problem is formulated as an optimization problem for the TCSC controller (as shown in Fig. 1). In this case, the washout time constant T_{WT} and the time constant of the two-stage lead-lag block T_{2T} and T_{4T} are prespecified. The controller gain K_T and time constant T_{1T} and T_{3T} of lead-lag compensator are to be determined applying PSO. As mentioned earlier, the aim of the TCSC-based controller is to minimize the power system oscillations after a disturbance to improve the stability. These oscillations are reflected in the deviation in the generator rotor speed ($\Delta\omega$).

The objective function considered here is an integral time absolute error of the speed deviations, i.e.,

$$J = \int_{t=0}^{t=t_1} |\Delta\omega| \cdot t \cdot \mathrm{d}t \tag{2}$$

The aim is to minimize this objective function to improve the system response in terms of the settling time and overshoot. In this optimization problem, the different parameters chosen are as follows:

Swarm size = 20, maximum number of generations = 100, $C_1 = C_2 = 2.0$, $w_{\text{start}} = 0.9$ and $w_{\text{end}} = 0.4$ [15]. The optimized values of TCSC-based controller parameters obtained by PSO are as follows:

$K_T = 62.9343$, $T_{1T} = 0.1245$ and $T_{3T} = 0.1154$.

3 Interval Type-2 Fuzzy Logic-based TCSC Controller

It is a well-known fact that the conventional fuzzy logic controller (type-1 FLC) has the limitations that, it cannot handle or accommodate the linguistic and numerical uncertainties associated with dynamical systems because its membership grade is crisp in nature. Type-2 fuzzy logic systems outperformed the type-1 fuzzy logic systems because of the membership functions of an IT2FLS are fuzzy and also contain a footprint of uncertainty (Fig. 3). IT2FLC design is based on the concept of interval type-2 fuzzy logic system. The structure of IT2FLC is same as the conventional fuzzy logic controller structure except, one type reducer block is introduced between the inference engine and defuzzifier block because the output of the inference engine is a type-2 output fuzzy set and before applying it to the defuzzifier for getting the crisp input, it has to be converted to a type-1 fuzzy set.

The block diagram of an IT2FLC is shown in Fig. 3b which contains five interconnected blocks, i.e., fuzzifier, rules, inference, type reducer, and defuzzifier. There is a mapping exist between crisp inputs to crisp outputs of the IT2FLS and is expressed as $Y = f(X)$. The principle of working of the IT2FLC is very much similar to the type-1 fuzzy logic controller (T1FLC). It is important to note that increasing the type of fuzzy system only enhances the degree of fuzziness of the system and all other principles of conventional fuzzy logic like inferencing procedure, defuzzification techniques holds good for both type [6].

In this problem, the conventional lead-lag compensator-based TCSC is used in the modified Phillips–Heffron model block diagram, and GTCSC(s) is replaced by an IT2FLC. First, the SMIB system model is simulated using a conventional T1FLC and then with IT2FLC. The rule base is same for both FLC and IT2FLC. The inputs considered here are speed ($\Delta\omega$) and its derivative ($\Delta\omega'$). The output is the change in conduction angle ($\Delta\sigma$). Triangular and gaussian type membership functions have been used for the mamdani-type FLC and IT2FLC, respectively. Centroid-type

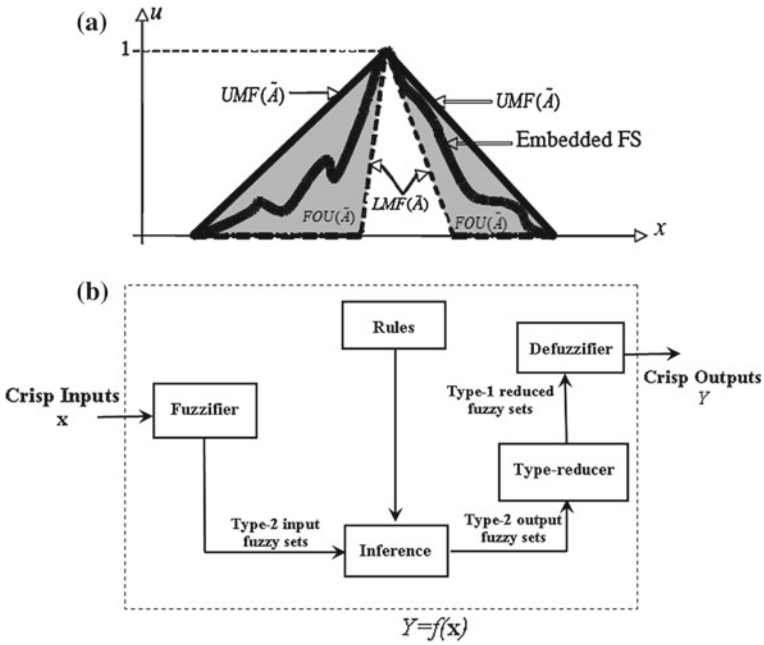

Fig. 3 **a** FOU (*shaded*), LMF (*dashed*), UMF (*solid*) and an embedded FS (*wavy line*) for IT2FSÃ. **b** Block diagram of IT2FLC [6]

Table 1 Rule base table for both FLC and IT2FLC

$\Delta\sigma$		$\Delta\omega \rightarrow$				
		NB	NS	ZO	PS	PB
$\Delta\omega'$	NB	NB	NB	NB	NM	NS
$\downarrow$	NS	NM	NS	NS	ZE	PS
	ZO	NM	NS	ZE	PS	PM
	PS	NS	ZE	PS	PS	PM
	PB	PS	PM	PB	PB	PB

Where NB-Negative Big, NS-Negative Small, ZO-Zero Error, PS-Positive Small and PB-Positive Big are the name of the membership functions

defuzzification method is used for the FLC design. The performance of the SMIB system is analyzed.

The performance of the controller is studied and is also validated at different operating conditions.

4 Results and Discussion

First, the SMIB power system model is simulated using the lead-lag compensator-based TCSC. The PSO algorithm was used to find the optimal values $K_T = 62.9343$, $T_{1T} = 0.1245$ and $T_{3T} = 0.1154$. Washout time constant T_{WT} and the time

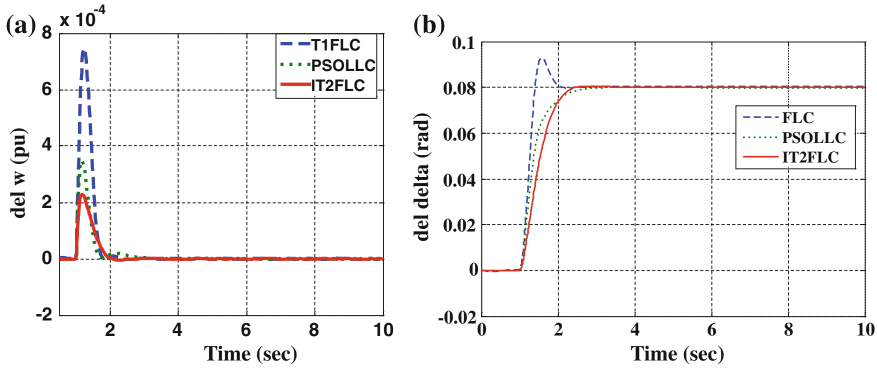

Fig. 4 **a** Rotor speed deviation. **b** Power angle deviation plot for 5 % step increase in mechanical power at nominal loading condition

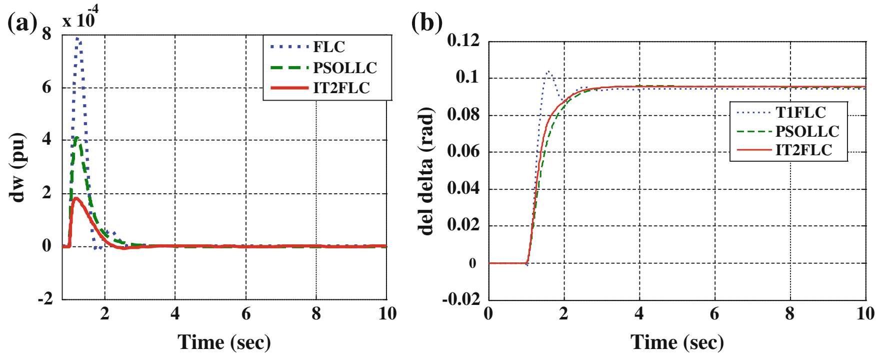

Fig. 5 **a** Rotor speed deviation. **b** Power angle deviation plot for 5 % step increase in mechanical power input with 50 % increase in line reactance at nominal loading

constant of the two-stage lead-lag block T_{2T} and T_{4T} are prespecified. These values are considered in the TCSC structure for simulation. Three loading conditions are taken, i.e., nominal, light, and heavy loading. The real (P) and reactive power (Q) values for the two loading conditions are as follows.

(1) Nominal loading (pu) → P = 0.9 and Q = 0.469 (2) Heavy loading (pu) → P = 1.02 and Q = 0.5941.

Second, the GTCSC(S) block of SMIB model is replaced by the conventional fuzzy logic controller designed with the principle as discussed in the Sect. 3. Third, the GTCSC(S) block of SMIB system is replaced by the IT2FLC designed with the procedure as depicted in previous section. The rule base as shown in Table 1 is designed based on the generalized performance of power system oscillations employing TCSC. The effectiveness and robustness of the controllers are also evaluated at (1) different loading conditions (2) disturbance of 5 % step increase in reference mechanical power input (3) variation of transmission line reactance.

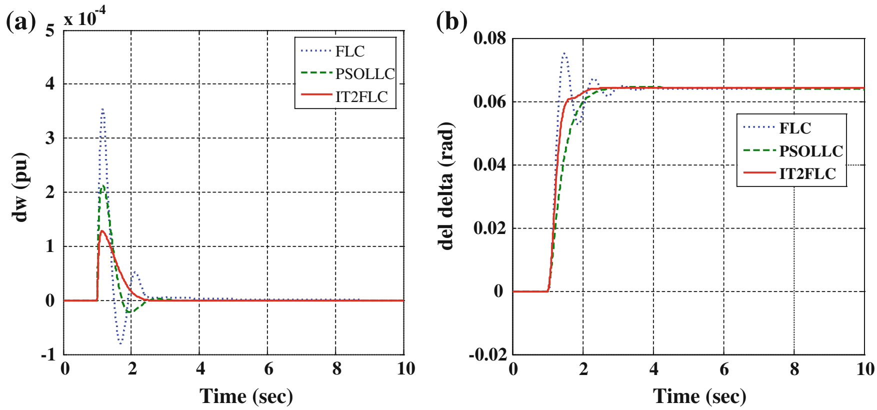

Fig. 6 **a** Rotor speed deviation. **b** Power angle deviation plot for 5 % step increase in mechanical power input at heavy loading with 10 % decrease in line reactance

Figures 4, 5 and 6 shows the rotor speed deviation and power angle deviation plots at disturbance of 5 % step increase in mechanical power input at different loading conditions and varying the transmission line reactance. It is analyzed from all the responses that the magnitude of overshoot and the settling time in all the speed deviation plots is less in case of IT2FLC compared to both PSOLLC and FLC. For the same condition, it is observed from the power angle deviation plots that there is no overshoot contributed by the PSOLLC and IT2FLC, but the IT2FLC response is faster compared to other two. FLC contributed some overshoot, but all are settling approximately at the same time.

It is found from all three results that the proposed controller is an effective and robust one compared to PSOLLC and FLC-based TCSC in providing good damping of low-frequency oscillations and to improve the system voltage profile. Although PSO-based algorithms are simple concept, easy to implement and computationally efficient, but there is possibility of trapped in local minima when handling more constrained problems due to the limited searching capacity.

5 Conclusion

In this paper, the performance of IT2FLC and FLC-based TCSC controllers are compared with a PSO optimized lead-lag compensator-based TCSC controller. The IT2FL-based TCSC controller surpasses the FL- and PSO-tuned TCSC controller performance at different loading conditions.

Appendix

All data are in per unit (pu) unless specified. Generator: $M = 9.26\,\text{s}$, $D = 0$, $X_d = 0.973$, $X_q = 0.55$, $X'_d = 0.19$, $T'_{\text{do}} = 7.76, f = 60\,\text{Hz}$, $X = 0.997$, Exciter: $K_A = 50$, $T_A = 0.05\,\text{s}$, TCSC: $X_{\text{TCSC0}} = 0.2169$, $X_C = 0.2X$, $X_P = 0.25X_C$.

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