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RESEARCH ARTICLE

Manoj Kumar PANDA, Gopinath PILLAI, Vijay KUMAR

An interval type-2 fuzzy logic controller for TCSC to improve the damping of power system oscillations

Abstract In this paper an interval type-2 fuzzy logic controller (IT2FLC) was proposed for thyristor controlled series capacitor (TCSC) to improve power system damping. For controller design, memberships of system variables were represented using interval type-2 fuzzy sets. The three-dimensional membership function of type-2 fuzzy sets provided additional degree of freedom that made it possible to directly model and handle uncertainties. Simulations conducted on a single machine infinite bus (SMIB) power system showed that the proposed controller was more effective than particle swarm optimization (PSO) tuned and type-1 fuzzy logic (T1FL) based damping controllers. Robust performance of the proposed controller was also validated at different operating conditions, various disturbances and parameter variation of the transmission line parameters.

Keywords power system oscillations, thyristor controlled series capacitor (TCSC), type-2 fuzzy logic system, interval type-2 fuzzy logic controller (IT2FLC)

1 Introduction

Uncertainty is limited within the definition of variables for type-1 fuzzy systems. It is not present in the definition of membership functions, although the membership function parameters are determined by the experience and knowledge of experts which vary from case to case [1]. Unlike the membership functions of type-1 fuzzy sets which are crisp because of the lagging in providing support for many kinds of uncertainty that appears in subjectively expressed knowledge of experts, a type-2 fuzzy set is characterized by a fuzzy membership function and provides additional degree of freedom that makes it possible to directly model and handle uncertainties [2].

Interval type-2 fuzzy logic controller (IT2FLC) was designed by exploring the property of interval type-2 fuzzy sets, which is a special type of type-2 fuzzy sets. The concept of type-2 fuzzy sets was introduced by Zadeh as an extension of classical type-1 fuzzy sets [3–5]. But from 1998, the real research on type-2 fuzzy sets was commenced by Karnik and Mandel, particularly on the mathematical operations of type-2 fuzzy sets and different steps involved in operation of type-2 fuzzy systems [6–9]. These significant contributions in type-2 fuzzy logic system had an impact on the researchers involved in fuzzy logic and its application. Till date, type-2 fuzzy logic systems have been applied in different areas of engineering and science such as equalization of nonlinear time varying channels [10], connection admission control in asynchronous transfer mode (ATM) networks [11], medical applications [12,13], control of flexible joint manipulator [14], signal processing [15], pattern recognition [16], classifier [17], traffic forecasting [18], and intelligent control [19].

Very few applications to type-2 fuzzy logic in power system were reported. These applications of IT2FLC, such as automatic voltage regulator design [20], power system stabilizer [21], fault current calculations of electrical power distribution system [22], control of a buck DC-DC converter [23], an IT2FLC for TCSC [24] for improving power system stability, proved to be an alternative of conventional fuzzy logic and other intelligent controllers when handling complex, nonlinear and uncertain systems. Literature survey revealed the importance and potential to outperform conventional fuzzy logic controllers, especially in dealing with uncertainties, disturbances and eliminating oscillations. Conventional fuzzy logic controllers appeared to be inferior in handling these issues because their membership function was crisp rather than fuzzy as in the case of type-2 fuzzy sets. The membership function plot of a T2FLS was three dimensional compared to the two

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Manoj Kumar PANDA (✉), Vijay KUMAR
Electronics & Computer Engineering Department, Indian Institute of Technology, Roorkee 247667, India
E-mail: pandadec@iitr.ernet.in

Gopinath PILLAI
Electrical Engineering Department, Indian Institute of Technology, Roorkee 247667, India

dimensional nature of its counterpart. The presence of this extra dimension provided additional degree of freedom to model the uncertainty [25]. Generally, IT2FLC had a smoother control surface around the origin than its counterpart, therefore, the same amount of disturbance would cause a smaller control signal change and hence reduced the risk of oscillation [26].

Flexible AC transmission systems (FACTS) are a technology to improve the quality of transmission with minimum investment on infrastructure, environment impact and implementation time compared to the construction of new transmission lines. FACTS controllers can be utilized to control power flow and enhance system stability. TCSC is one of the important members of the FACTS family that is increasingly applied with transmission lines by the utilities in modern power systems. It can play various roles in the operation and control of power systems such as scheduling power flow, decreasing unsymmetrical components, reducing net loss, providing voltage support, limiting short circuit currents, mitigating sub synchronous resonance, damping the power oscillations, and enhancing transient stability [27,28].

Over the years, significant work have been conducted in developing TCSC models with various control strategies such as pole placement [29,30], H_∞ control [31], nonlinear control [32], adaptive control [33,34], heuristic optimization based [35,36], and fuzzy controller based techniques [37].

In this paper type-2 fuzzy logic was used to design a damping controller for TCSC. Gaussian interval type fuzzy sets were used for representation of the system variables. The study system was a single machine infinite bus (SMIB) system. The generator speed variation was used as the feedback signal to control the local mode oscillations. The performance of the proposed type-2 FLC was compared with the performances of PSO optimized lead lag compensator (PSOLLC) and a type-1 fuzzy logic (T1FL) based damping controllers. The TCSC controller and the proposed IT2FL based TCSC controller were applied for damping the power oscillations. Simulation was conducted for the SMIB system. The change in rotor speed deviation, the change in rotor angle deviation and the change in terminal voltage performance characteristics were compared. The effectiveness of the proposed controller was also tested at different small disturbances and transmission line reactance variation for the three loading conditions.

2 IT2FLC

It is a well known fact that the conventional FLC (type-1 FLC) 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 outperform the T1FL systems in the following ways:

1) Since the membership functions of an IT2FLS are fuzzy and contain a footprint of uncertainty (FOU) (Fig. 1) which is nothing but the area covered between the lower and upper membership functions and represents the capacity to handle the degree of uncertainty, they can model and handle both linguistic and numerical uncertainties associated with the inputs and outputs of the fuzzy logic controller (FLC). Therefore, the FLC based on IT2FS will have the potential to outperform the T1FLC with respect to uncertainty [38].

2) As the embedding of a large number of type-1 fuzzy sets results in a type-2 fuzzy set, the use of such a large number of type-1 fuzzy sets to describe the input and output variables allows for a full description of the analytical control surface as the addition of extra levels of classification gives much smoother control surface and response [25].

3) The extra degree of freedom provided by the FOU enables a type-2 FLS to produce outputs that cannot be achieved by type-1 FLS with the same number of membership functions. It has been shown that a type-2 fuzzy set may give rise to an equivalent type-1 membership grade i.e. negative or larger than unity. Thus a T2FLS is able to model more complex input-output relationships than its type-1 counterparts and thus can give a better control response [38].

The mathematical analysis of interval type-2 fuzzy set was well illustrated in Ref. [39]. Figure 1 represents the triangular interval type-2 membership function of a fuzzy set $\tilde{A}$. The uncertainty about $\tilde{A}$ is conveyed by the union of all the primary memberships, which is called the FOU of $\tilde{A}$, as shown in the shaded region (Fig. 1) [39].

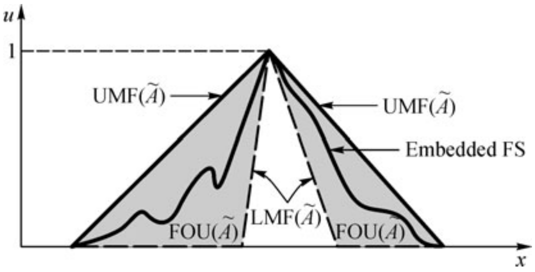

Fig. 1 Pictorial representation of triangular IT2FS $\tilde{A}$

The IT2FLC design is based on the concept of interval type-2 fuzzy logic system. The structure of IT2FLC is the same as that of the conventional FLC except that 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 output, it has to be converted to a type-1 fuzzy set. The block diagram of an IT2FLC is depicted in Fig. 2 [39] which contains five interconnected blocks i.e. fuzzifier, rules, inference, type reducer and defuzzifier. There is a mapping between crisp inputs and crisp outputs of the IT2FLS, which is expressed

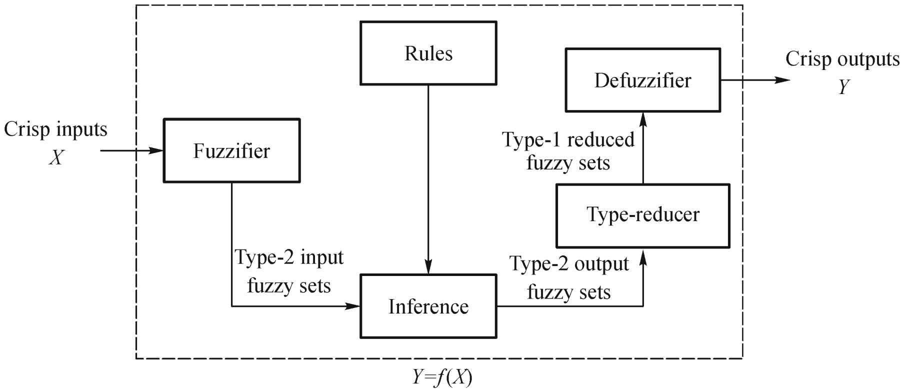

Fig. 2 Structure of IT2FLC

as $Y = f(X)$. The principle of the working of the IT2FLC is very much similar to that of the T1FLC. It is important to note that increasing the type of fuzzy system only enhances the degree of fuzziness of the system while other principles of conventional fuzzy logic such as inferencing procedure, defuzzification techniques hold good for both types [20,39].

3 System modeling with TCSC

The single-machine infinite-bus power system demonstrated in Fig. 3 was considered in this study. The system has a TCSC installed in the transmission line. In Fig. 3, X_T and X_L represent the reactance of the transformer and the transmission line, respectively, whereas V_T and V_B are the generator terminal and infinite bus voltage, respectively. The nonlinear differential equations of the SMIB system with TCSC are expressed as follows and detail notations with parametric values can be found in Ref. [40].

$$\left.\begin{aligned}
\dot{\delta} &= \omega_b \Delta\omega,\\
\dot{\omega} &= \frac{1}{M}(P_m - P_e),\\
\dot{E}'_q &= \frac{1}{T'_{do}}(-E_q + E_{fd}),\\
\dot{E}'_{fd} &= \frac{K_A}{1+sT_A}(V_R - V_T),
\end{aligned}\right\}\tag{1}$$

where

$$\left.\begin{aligned}
P_e &= \frac{E'_q V_B}{X_{d\Sigma'}}\sin\delta - \frac{V_B^2 (X_q - X'_d)}{2X_{d\Sigma'} X_{q\Sigma'}}\sin 2\delta,\\
E_q &= \frac{X_{d\Sigma} E'_q}{X_{d\Sigma'}} - \frac{(X_q - X'_d)}{X_{d\Sigma'}} V_B \cos\delta,\\
V_{Td} &= \frac{X_q V_B}{X_{q\Sigma'}}\sin\delta,\ V_{Tq} = \frac{X_{eff} E'_q}{X_{d\Sigma'}} + \frac{V_B X'_d}{X_{d\Sigma'}}\cos\delta,\\
V_T &= \sqrt{(V_{Td}^2 + V_{Tq}^2)},\\
X_{eff} &= X_T + X_L - X_{TCSC}(\alpha),\ X_{d\Sigma'} = X'_d + X_{eff},\\
X_{q\Sigma'} &= X_q + X_{eff},\quad X_{d\Sigma} = X_d + X_{eff}.
\end{aligned}\right\}\tag{2}$$

The excitation system used in this work is IEEE type ST1A excitation system which is displayed in Fig. 4 [35].

The Phillips-Heffron model of the power system with FACTS devices was obtained by linearizing Eqs. (1) and (2) around the operating conditions of the power system [35]. The linearized equations are

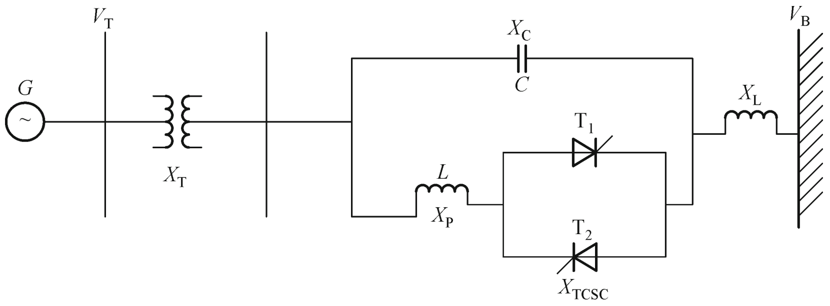

Fig. 3 SMIB system with TCSC

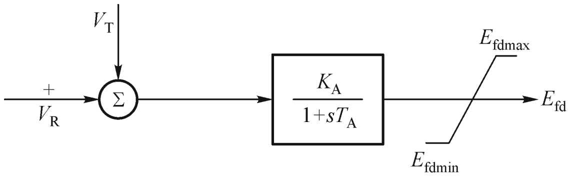

Fig. 4 IEEE ST1A excitation system

$$\left.\begin{aligned}
\Delta\dot{\delta} &= \omega_b\Delta\omega,\\
\Delta\dot{\omega} &= \frac{-K_1\Delta\delta - K_2\Delta E_q' - K_P\Delta\sigma - D\Delta\omega}{M},\\
\Delta\dot{E_q'} &= \frac{-K_3\Delta E_q' - K_4\Delta\delta - K_Q\Delta\sigma + \Delta E_{fd}}{T_{do}'},\\
\Delta\dot{E'_{fd}} &= \frac{-K_A(K_5\Delta\delta + K_6\Delta E_q' + K_V\Delta\sigma) - \Delta E_{fd}}{T_A},
\end{aligned}\right\} \quad (3)$$

where $K_1 = \frac{\partial P_e}{\partial\delta}, K_2 = \frac{\partial P_e}{\partial E_q'}, K_P = \frac{\partial P_e}{\partial\sigma}, K_3 = \frac{\partial E_q}{\partial E_q'}, K_4 = \frac{\partial E_q}{\partial\delta}, K_Q = \frac{\partial E_q}{\partial\sigma}, K_5 = \frac{\partial V_T}{\partial\delta}, K_6 = \frac{\partial V_T}{\partial E_q'}, K_V = \frac{\partial V_T}{\partial\sigma}$.

Using the set of linear equations as represented in Eq. (3), the Phillips-Heffron modified model is exhibited in Fig. 5.

The TCSC damping controller consisted of a gain block having a gain K_T, a washout block, which was a high pass filter to allow signals associated with oscillations in the 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

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

where y is the output signal and x is the input signal of the TCSC controller. The TCSC controller (Fig. 6) was connected in the SMIB system model, as shown in Fig. 5. The objective of the TCSC controller was to minimize the power system oscillations after a disturbance to improve the stability by contributing a damping torque. The damping torque contributed by the TCSC was divided into two parts. The first part K_P, which was referred to as the direct damping torque was directly applied to the electromechanical oscillations loop of the generator. The second part K_Q and K_V was known as indirect damping torque and applies through the field channel of the generator [36].

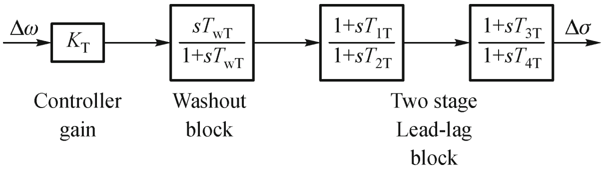

Fig. 6 TCSC controller block diagram

4 Proposed IT2FLC design for TCSC

In this problem, the conventional lead lag compensator based TCSC used in the modified Phillips- Heffron model block diagram, $G_{TCSC}(s)$ was replaced by an IT2FLC. The SMIB system model was simulated first using a conventional type-1 FLC and then with IT2FLC. The rule base was the same for both FLC and IT2FLC. The inputs considered were speed ($\Delta\omega$) and its derivative ($\Delta\acute{\omega}$). The output was the change in conduction angle ($\Delta\sigma$).

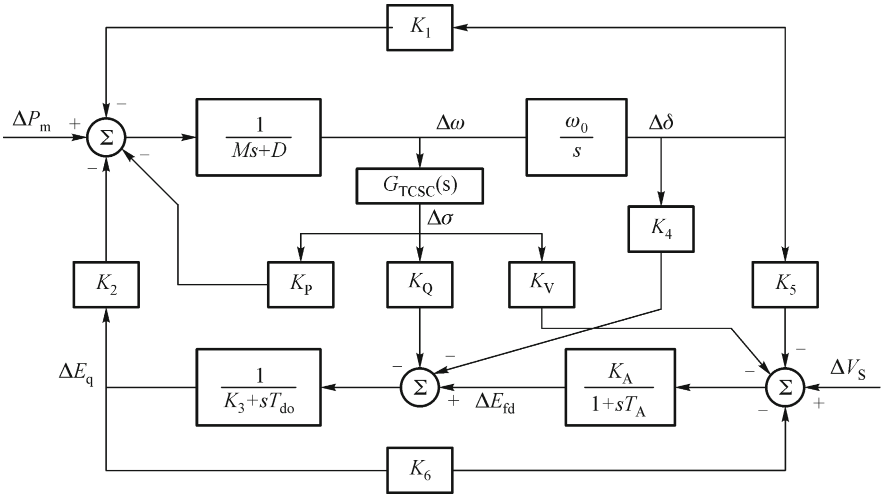

Fig. 5 Modified Phillips-Heffron model of SMIB system using TCSC [41]

Triangular type membership functions were used for the mamdani type FLC design. Five membership functions were chosen for each input and control vector. The centroid type defuzzification method was used for the FLC design. The performance of the SMIB system was analyzed.

For the design of IT2FLC as TCSC was applied in the SMIB model, the same rule base as used in the design of FLC, shown in Table 1, was implemented. The membership function plots were given in Fig. 7. Gaussian membership functions were chosen for both input and output variables, respectively. The meet operation-min method, join operation-max method, meet implication-min method, and join aggregation-max method were used for different operations in the IT2FLC design. For type reduction and defuzzification, the centroid method was used. The detailed mathematical analysis of the procedure could be found in Ref. [39].

Table 1 Rule base table for both FLC and IT2FLC

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

Notes: NB–negative big; NS–negative small; ZO–zero error; PS–positive small; PB–Positive big is the name of the membership functions.

Five types of reduction methods such as centroid, height, centroid of sets, modified height and center of sums were described in Ref. [6]. These methods were very much similar to the usual defuzzification techniques applied in T1FLS. The centroid of a type-2 fuzzy set was a type-1 fuzzy set as defined and derived in Ref. [8]. Although the computation of the centroid of a type-2 fuzzy set was a little bit difficult, an exact simple iterative method for IT2FS was reported in Ref. [8] and was possible because the centroid of an IT2FS was an IT1FS, and such sets were completely characterized by their left (Y_l) and right (Y_r) end points; hence, the computation of the centroid of an IT2FS set only required the computation of those two end-points.

The Karnik and Mendel algorithm [8] was applied to compute y_l and y_r. The defuzzified output of an IT2FLS was simply the average of y_l and y_r, i.e.,

$$y = \frac{(y_\mathrm{l}) + (y_\mathrm{r})}{2}. \tag{5}$$

This is a crisp output and can be applied to the input of the plant. In the proposed controller design, this method was applied for both the type reduction and the defuzzification purpose.

The performance of the controller was studied and validated at different operating conditions. The proposed controller performance was compared with the PSO based tuned lead-lag compensator [36] in which the problem was formulated as an optimization problem for the TCSC controller. In this case (Fig. 6), the washout time constant T_wT and the time constant of the two stage lead-lag block T_2T and T_4T were pre-specified. The controller gain K_T and time constant T_1T and T_3T of the lead lag compensator were determined by applying PSO. As mentioned earlier, the aim of the TCSC based controller was to minimize the power system oscillations after a disturbance to improve the stability. These oscillations were reflected in the deviation in the generator rotor speed ($\Delta\omega$). The objective function considered here was an integral time absolute error of the speed deviations, i.e.,

$$J = \int_0^{t_1} |\Delta\omega| t \mathrm{d}t. \tag{6}$$

The aim was to minimize this objective function to

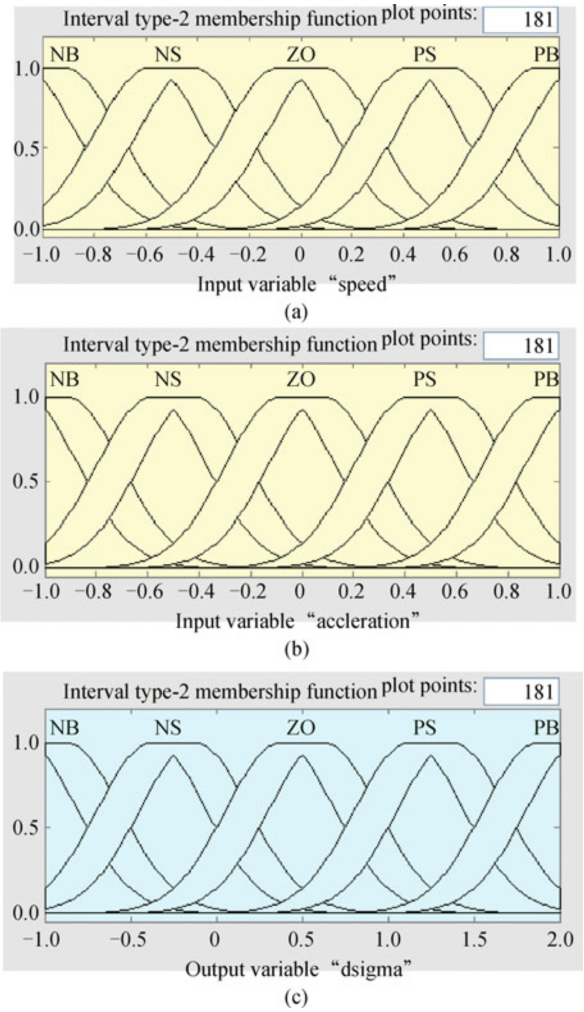

Fig. 7 Membership function plot for I/P and O/P of IT2FLC
(a) For speed deviation; (b) for acceleration; (c) for sigma deviation

improve the system response in terms of the settling time and overshoot. In this optimization problem, the different parameters chosen are: swarm size = 20, maximum number of generations = 100, $C_1 = C_2 = 2.0$, $w_{\text{start}} = 0.9$ and $w_{\text{end}} = 0.4$ [36]. The optimized values of TCSC based controller parameters obtained by PSO are $K_{\text{T}} = 62.9343$, $T_{1\text{T}} = 0.1245$ and $T_{3\text{T}} = 0.1154$.

5 Results and discussion

First, the SMIB power system model was simulated using the lead lag compensator based TCSC. The PSO algorithm was used to find the optimal values $K_{\text{T}} = 62.9343$, $T_{1\text{T}} = 0.1245$ and $T_{3\text{T}} = 0.1154$. The washout time constant T_{wT} and the time constant of the two stage lead-lag block $T_{2\text{T}}$ and $T_{4\text{T}}$ were prespecified. These values were considered in the TCSC structure for simulation. Three loading conditions, i.e., nominal, light and heavy loading were considered, The real (P) and reactive power (Q) values for the three loading conditions considered were nominal loading (pu) $\rightarrow$ $P = 0.9$ and $Q = 0.469$; light loading (pu) $\rightarrow$ $P = 0.4$ and $Q = 0.1446$; and heavy loading (pu) $\rightarrow$ $P = 1.02$ and $Q = 0.5941$.

The constants (K_1–K_6) and (K_{P}, K_{Q} and K_{V}), as shown in the SMIB model in Fig. 5, were computed using Eq. (3) for all loading conditions and substituted in the simulation model.

Secondly, the $G_{\text{TCSC}}(s)$ block of the SMIB model was replaced by the conventional FLC designed in the same manner as IT2FLC. The values of the constants used in the modified Phillips-Heffron model based SMIB system with TCSC were the same for all controllers at particular loading conditions.

Thirdly, the $G_{\text{TCSC}}(s)$ block of the SMIB system was replaced by the IT2FLC designed with the procedure as depicted in Section 4. The rule base as shown in Table 1 was designed based on the generalized performance of power system oscillations by employing TCSC. The effectiveness and robustness of the controllers were evaluated at (i) different loading conditions, (ii) disturbance of a 5% step increase in reference mechanical power input, (iii) variation of transmission line reactance, and (iv) disturbance of a 5% step increase in reference voltage.

Figure 8 shows the response of rotor speed deviation for a 5% step increase in mechanical power input at nominal loading condition. The magnitude of oscillation and settling time were reduced with the proposed IT2FLC compared to both PSOLLC and FLC.

Figure 9 shows the power angle deviation response for a 5% step increase in mechanical power input at nominal loading. There is no overshoot present in both PSOLLC and the proposed IT2FLC. The settling time of both FLC and IT2FLC was less than that of PSOLLC.

Figure 10 shows the terminal voltage response for a 5% step increase in mechanical power input at nominal loading. The magnitude of oscillation and settling time of the proposed IT2FLC was less than that of both PSOLLC and FLC.

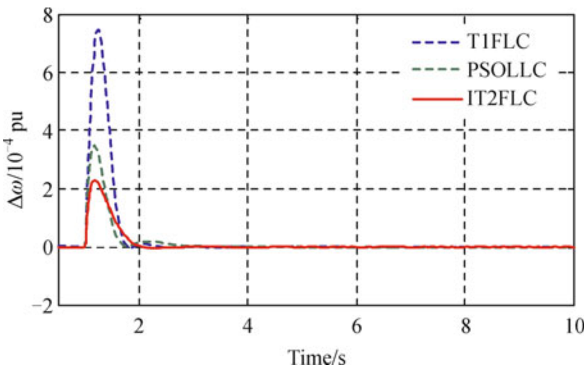

Fig. 8 Speed deviation ($\Delta\omega$) system response for a 5% step increase in mechanical power input at nominal loading

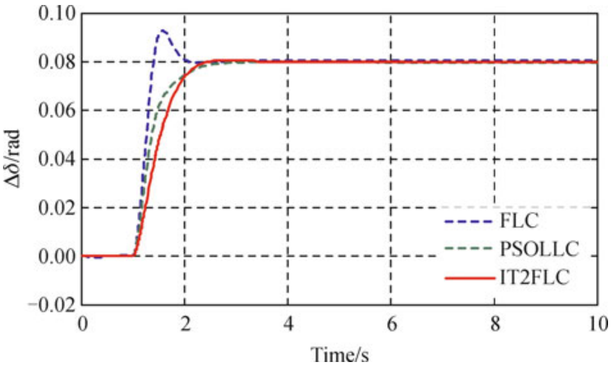

Fig. 9 Power angle deviation ($\Delta\delta$) system response for a 5% step increase in mechanical power input at nominal loading

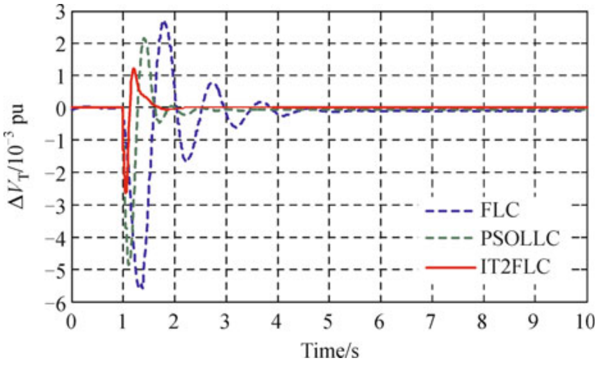

Fig. 10 Terminal voltage (ΔV_{T}) system response for a 5% step increase in mechanical power input at nominal loading

The effectiveness of the controllers was validated by varying the transmission line reactance, because by doing so the constant values i.e. from K_1 to K_6 in the SMIB model would also change. Figure 11 shows the speed deviation response for a 5% step increase in mechanical power input at light loading with a 50% increase in line

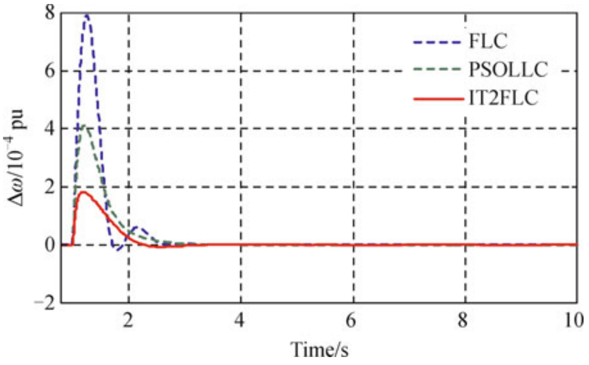

Fig. 11 Speed deviation (Δω) system response for a 5% step increase in mechanical power input at light loading with a 50% increase in line reactance

reactance. Both the overshoot and settling time were less for the proposed IT2FLC compared to PSOLLC and FLC. Figure 12 shows the power angle deviation response for a 5% step increase in mechanical power input at light loading with a 50% increase in line reactance. In this case, the responses of all the controllers were settled approximately at the same time and there were some oscillations present in the case of the FLC response.

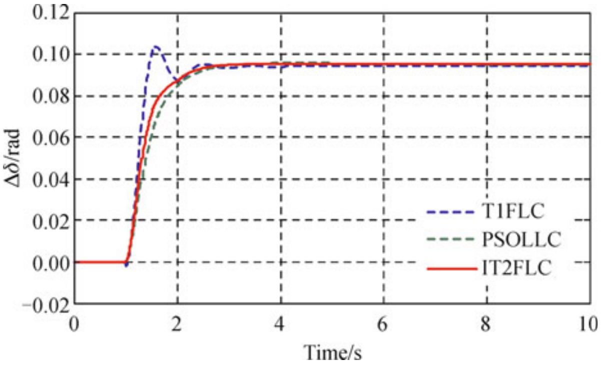

Fig. 12 Power angle deviation (Δδ) system response for a 5% step increase in mechanical power input at light loading with a 50% increase in line reactance

Figure 13 shows the terminal voltage system response for a 5% step increase in mechanical power input at light loading with a 50% increase in line reactance. In this case, although both the positive and negative overshoot magnitude for PSOLLC and the proposed IT2FLC were approximately the same, IT2FLC had less rise time and settling time than the other two controllers, therefore, it is faster than the other two. The PSOLLC and FLC response were not settled perfectly at the desired value.

Figure 14 shows the speed deviation response for a 5% step increase in mechanical power input at heavy loading with a 10% decrease in transmission line reactance. Although all the controller responses were settled at the same time, IT2FLC had less positive overshoot magnitude and no negative overshoot was present, whereas PSOLLC and FLC contributed less negative overshoot and more positive overshoot compared to IT2FLC.

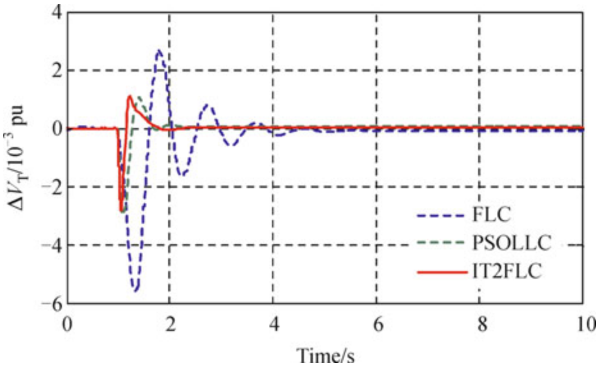

Fig. 13 Terminal voltage (ΔV_T) system response for a 5% step increase in mechanical power input at light loading with a 50% increase in line reactance

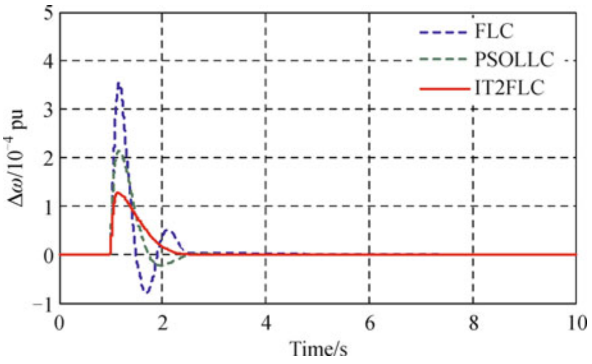

Fig. 14 Speed deviation (Δω) system response for a 5% step increase in mechanical power input at heavy loading with a 10% decrease in line reactance

Figure 15 shows the power angle deviation plot for a 5% step increase in mechanical power input at heavy loading with a 10% decrease in line reactance. The proposed IT2FLC and PSOLLC response were settled around the same time, but the IT2FLC response was faster. The FLC

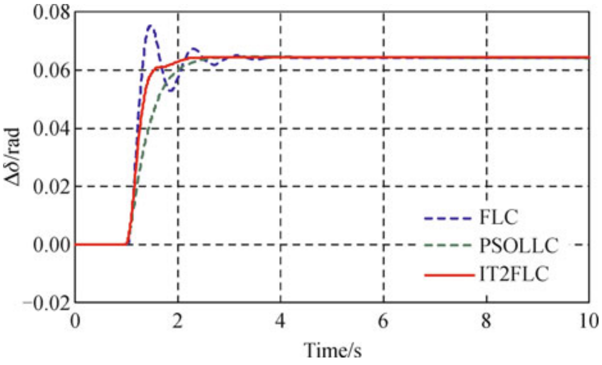

Fig. 15 Power angle deviation (Δδ) system response for a 5% step increase in mechanical power input at heavy loading with a 10% decrease in line reactance

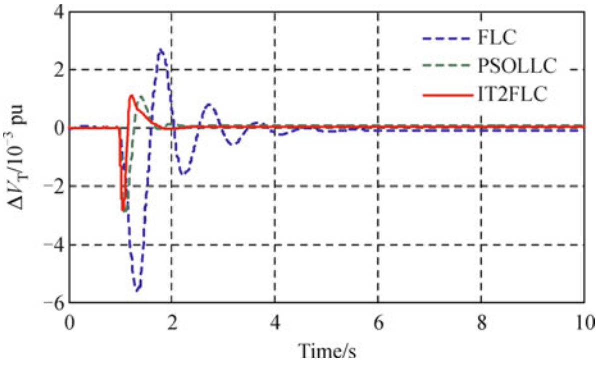

Fig. 16 Terminal voltage (ΔV_T) system response for a 5% step increase in mechanical power input at heavy loading with a 10% decrease in line reactance

output was perfectly settled, but contributed some oscillations and settled at more time compared to the other two. The terminal voltage response at heavy loading condition for a 5% step increase in mechanical power input with a 10% decrease in transmission line reactance is shown in Fig. 16. It was clearly indicated that the IT2FLC voltage plot had less positive overshoot, less negative overshoot, and less settling time compared to the PSOLLC and FLC response.

Furthermore, to explore the effectiveness of the proposed controller, an additional disturbance of a 5% step increase in reference voltage setting was applied to the SMIB model. The speed deviation plot for this case is shown in Fig. 17. The IT2FLC plot had considerably less positive overshoot and settling time without contributing any negative overshoot compared to PSOLLC and FLC.

Figure 18 shows the power angle deviation response for heavy loading with a 5% step increase in reference voltage setting. The IT2FLC response was faster without contributing any overshoot. The settling time for both PSOLLC and IT2FLC was approximately the same. The FLC response had a large amount of overshoot but did not reach the settle value. The terminal voltage system response for heavy loading with a 5% increase in reference voltage setting is shown in Fig. 19. In this case, all the controllers contributed approximately the same amount of positive overshoot. The IT2FLC response was settled early compared to the other two. Both PSOLLC and IT2FLC did not contribute any negative overshoot. FLC had some negative overshoot but the settling time was very high and lay behind the settled value.

The prime reason behind the best performance obtained by IT2FLC compared to its counterpart in applying the proposed IT2FLC based TCSC for damping the oscillations in the SMIB system is that IT2FLC is better able to cope with uncertainties in TCSC and SMIB parameter selection at different loading conditions. Besides, IT2FLC has an extra mathematical dimension due to its FOU and hence offers more design freedom. Furthermore, it has a smooth control surface around the origin, and consequently, the same amount of disturbance will cause a smaller control signal change resulting in reduced risk of oscillation.

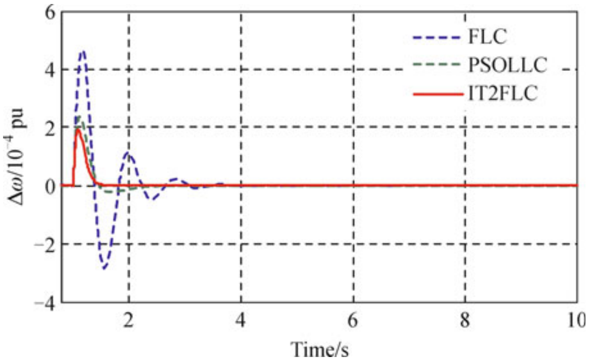

Fig. 17 Speed deviation ($\Delta\omega$) system response for heavy loading with a 5% step increase in reference voltage setting

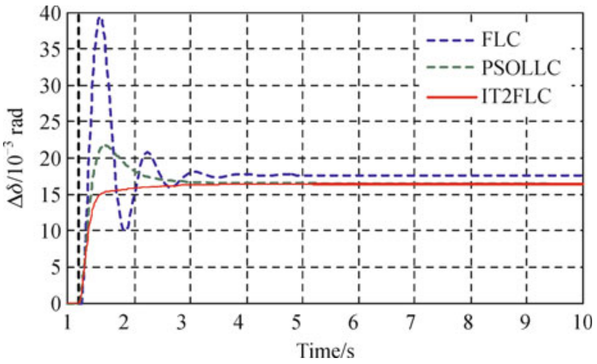

Fig. 18 Power angle deviation ($\Delta\delta$) system response for heavy loading with a 5% step increase in reference voltage setting

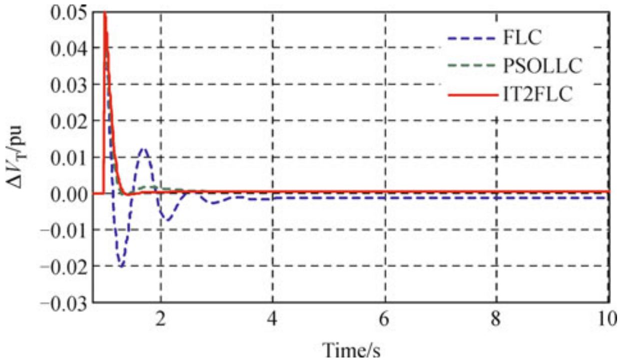

Fig. 19 Terminal voltage (ΔV_T) system response for heavy loading with a 5% increase in reference voltage setting

6 Conclusions

Interval type-2 fuzzy logic was used to design a supplementary controller for TCSC to damp the power system oscillations. The new third dimension of type-2 fuzzy logic provided additional degree of freedom that made it possible to directly model and handle uncertainties. The simulations showed that TCSC supplementary controller using the IT2FLC outperformed FLC. The performance of IT2FLC and FLC based TCSC controllers were also compared with a PSO optimized lead lag compensator based TCSC controller. The effectiveness and robustness of the proposed IT2FLC was tested at different loading conditions, at various disturbances and transmission line parameter variations. It was found that in all loading conditions the performance of IT2FLC was better in providing good damping of low frequency oscillations and to improve the system voltage profile.

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Notations

X_C	Capacitive reactance of TCSC
X_P	Inductive reactance of TCSC
k	Compensation ratio
α	Firing angle of TCSC
X_T	Transformer reactance
V_T	Terminal voltage of generator
V_B	Infinite bus voltage
X_L	Reactance of transmission line
δ	Rotor angle of generator
ω	Rotor speed of generator
P_m	Mechanical power input to generator
P_e	Electrical power output of generator
M	Generator inertia constant
D	Damping coefficient of generator
σ	TCSC conduction angle
X_d	d-axis synchronous reactance of generator
K_A	Gain of excitation system
X'_d	d-axis transient reactance of generator
T_A	Time constant of excitation system
E_{fd}	Excitation system voltage
E'_q	Generator terminal voltage
ω_b	Synchronous speed of generator
X_q	q-axis synchronous reactance of generator
X'_q	q-axis transient reactance of generator

Appendix

All the data are in per unit (pu) unless specified.

Generator: $M = 9.26$ s, $D = 0$, $X_d = 0.973$, $X_q = 0.55$, $X'_d = 0.19$, $T'_{do} = 7.76$, $f = 60$, $X = 0.997$. Exciter: $K_A = 50$, $T_A = 0.05$ s, TCSC: $X_{TCSC0} = 0.2169$, $X_C = 0.2X$, $X_P = 0.25X_C$.

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