Interval Fuzzy-PSS Using Gauss-2 Membership Function to Enhance Small-Signal Stability

I. Made Ginarsa(✉), I. Made Ari Nrartha, Agung Budi Muljono, Ida Ayu Sri Adnyani, Sultan Sultan, and Ni Made Seniari

Department of Electrical Engineering, University of Mataram, Mataram, NTB, Indonesia
{kadekgin,nrartha,agungbm,adnyani,sultandarma, seniari_nimade}@unram.ac.id

Abstract. Interval type-2 fuzzy (IT2F) model develops to substitute conventional control in power system (PS). The PS is operated to serve the consumer according to load demand. Load fluctuation on the PS is a real situation and can't be avoided. The load fluctuation causes rotor oscillation on machine. Moreover, instability problem can occur if this oscillation is not quickly to damp. The IT2F-based algorithm is developed to replace conventional power system stabilizer (PSS) function. The IT2F is implemented in this research because it simple and not need exactly calculation of plant model. A single machine and multi-machine power systems are applied to assess the performance of the IT2F-PSS. This IT2F-PSS is constructed by two inputs and an output. Three membership functions (MF) Gauss-2 type are used for respective inputs. Five MFs constant type are used for output. The values of fuzzy parameter are tuned properly based on the knowledge and experience the fuzzy developer. Simulations on the case studies provide enhancement the response of rotors speed and angle. The IT2F-PSS responses are assessed on peak overshoot and settling time.

Keywords: Gauss-2 · Interval Type-2 Fuzzy · stability improvement · rotor oscillation · reducing of settling time

1 Introduction

Modern power systems are complex systems that consist of some group of machines, where they working together to supply load that spread in wide-range area. The power systems are operated on synchronous mode in frequency 50/60 Hz. In power system operation, continuity of power plant or generator to supply load through power networks are one of concern operator in power companies. Some disturbances also commonly occur in power operation and can't be avoided, such as: Disconnect of network from the system, short circuit fault or load change. Intelligent control is an attractive control model that this control is simple to be implemented and do not need detailed mathematical model of system that they controlled. On-line assessment of large-PS is conducted using convolution neural-network. Data of bus voltage phasor sample are taken from phasor measurement unit and these data are used to predict the status of the PS. Status of the

S. Sugiman et al. (Eds.): MIMSE-M-E 2022, AER 216, pp. 180–192, 2023.
https://doi.org/10.2991/978-94-6463-078-7_20

PS are defined as: Stable, aperiodic unstable or oscillation unstable [1]. Power system stabilizer (PSS) is a device that wide-applied to stable of power system. New type digital PSS is introduced to minimize oscillatory of rotor-speed/angle in local and inter-area modes [2]. Generic and multi-band (MB) PSSs are applied to optimize reactive power compensation on wind-hydro distributed generators. The MB-PSS is able to work better than the generic PSS on various unsymmetrical faults and voltage level points [3]. Ant bee colony method is proposed to optimize the PSS parameter and is tested on single machine [4]. Also, the PSS is designed using adaptive fuzzy control to improve single machine [5] and indirect adaptive fuzzy without to know it non-linear function, but the control is structured using linguistic variables [6]. Linear matrix in-equality combined by robust h-infinity control to damp low frequency on variation of transmission parameter, real and reactive powers [7]. Also, the robust PSS design is realized on real-time to enhance performance and to reduce of disturbance effect in multi-machine [8]. Optimal PSS based on linear quadratic regulator design and phase lead-lag compensator to damp low frequency on multi-machine power system [9]. Gradient based meta heuristic optimal method such as: Gravitational search algorithm, bat algorithm, particle swarm optimization and steepest descent methods are applied to optimize the PSS parameters [10]. Instability detection in PS due to high penetration by wind-turbine sources is explored using innovative matrix based on potential energy surface [11]. Some application of intelligent control such as: Adaptive neuro-fuzzy inference system (ANFIS) model for enhancement of power system stability [12], transient response improvement of rectifier in high voltage direct current [13]. Stability effect of rotary-frequency based converter is implemented as the PSS in 50/60 Hz PS [14]. The Interval type-2 fuzzy is a linguistic model that is used in wide range such as power system stabilizer to improve stability of single machine [15], multi machine [16] and large-scale PS [17]. The IT2F also is used for micro-hydro and diesel PS on Lombok System [18]. Type-2 fuzzy PSS is tuned using sliding surface approach to damp rotor oscillation on wide-area system. The sliding surface is optimized by genetic algorithm [19]. Some methods are reported in PSS designed and the effectiveness of their performance, it is potential to propose PSS based on type-2 fuzzy model. The systematic writing of the paper: Simple power system using single machine connected to infinite bus and nine-bus 3-machine systems is explained in Sect. 2. In Sect. 3, we explain concept of PSS and interval fuzzy-based PSS. Simulation results for a single machine and multi machine models are explored in Sect. 4. Finally, the conclusion and future works are provided in Sect. 5.

2 Simple Power System

Commonly, a power system is built some components such as: Power plant, transmission/distribution and load, and in reality, power systems are the complex and complicated system in the world. In power plant, coal (chemical energy) is burned and this energy is used to produces steam under high heat and pressure. The steam energy is released to rotate steam turbine. The steam turbine shaft is coupled to the generator. In synchronous generator, mechanical power in rotation form is converted into electrical power. In generator the energy balance between electrical and mechanical energies occurred. When the energy balancing is disturbed due to short circuit fault or change of load, the minus

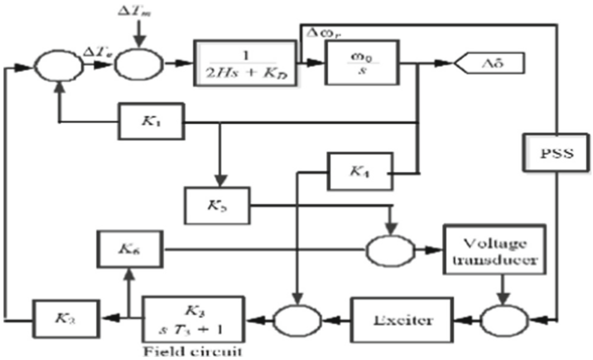

Fig. 1. Synchronous machine model for small-signal stability study.

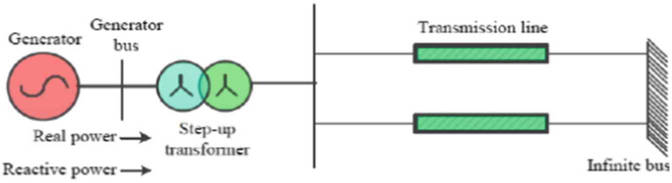

Fig. 2. One-line diagram of a single machine.

or surplus energy in generator is released by accelerating or decelerating of rotor speed and rotor angle. This process is illustrated by diagram block as in Fig. 1. In order to simplified representation, the PS, the PS is modeled by one-line diagram. Two examples are used for PSS applied: A single machine and 3-machine 9-bus power systems.

2.1 One-Line Representation of a Single Machine

Large and complex power systems can be represented into a voltage source, reactance behind the voltage for generator, external reactance for step-up transformer and transmission-line, and infinite-bus. The power system is taken from [20] Example 12.3 pp. 752 and is shown in Fig. 2. The generator unit capacity and voltage ratings: 4 $\times$ 555 = 2220 MVA and 24 kV, respectively. The generator unit and the system have frequency at 60 Hz.

2.2 One-Line Diagram of 9-Bus 3-Machine System

Large power systems are commonly supplied by more than one generator, where the WSCC system is considered as example for calculation of small signal stability multi-machine. The system is depicted in Fig. 3. That system using 100 MVA based with frequency system is 60 Hz. Machine 1 was a hydro generator and this bus was treated as the slack (reference) bus. While, Machine 2 and 3 were thermal generators and the buses were treated as PV type bus. Data for generators, exciters and bus voltages after load-flow process are given in [21].

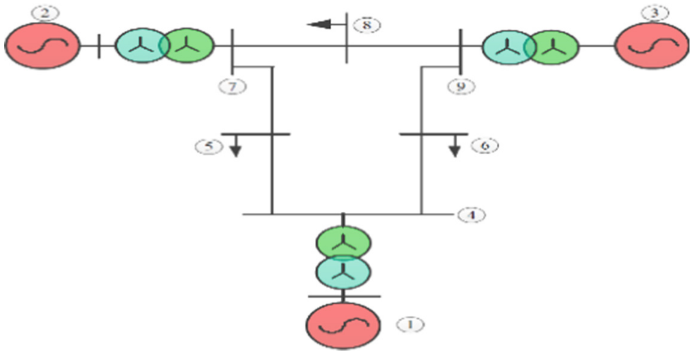

Fig. 3. Simplifier of WSCC system.

3 Development of PSS Model Using Type-2 Fuzzy

3.1 Conventional and IT2F PSS

Generally, PSS is a device that inserted in synchronous generator to produce stabilizer signal. This signal is used to damp rotor oscillation by modulating exciter device of the generator. We use rotor speed and stabilizer voltage signals as input and output, respectively. Diagram block of lead-lag PSS is shown Fig. 4(a). While, illustration of IT2F-PSS scheme is depicted in Fig. 4(b). It is shown that the IT2F-PSS inputs are rotor speed and its derivative signals. The signals are passed through multiplexer before enter fuzzy control device.

3.2 Fuzzy Logic System

Moreover, development of fuzzy type-1 principle to handle the not certain and not precision is type-2 fuzzy model [22]. We use triangular MF as example to describe type-2 fuzzy as shown in Fig, 5. Based on Fig. 5, it is shown that the x-axis is location of triangular MFs. There are exactly exist N triangle and at each x value, there is increased to N MF grade from $MF_1(x)$ until $MF_N(x)$ and respective of MF grade is assigned by weighting at $W_{x'1}$, $W_{x'2}$ … $W_{x'N}$. To illustrate of this MF grade, it is shown in Fig. 6. These weight values are connected to each triangle's grade at the x value. The results are collection grade in $\{((MF_i(x), W_{xi}), i = 1\ldots N\}$ function forms. So, it is resulted

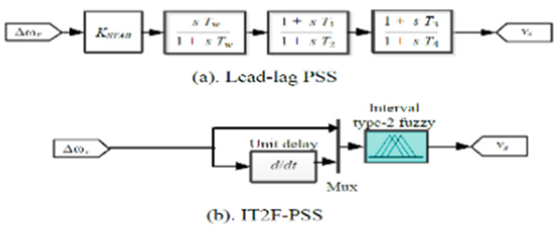

Fig. 4. Power system stabilizer diagram block.

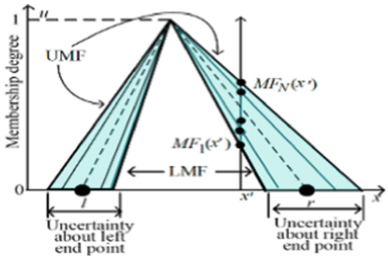

Fig. 5. Uncertainty intervals on base end-point (l and r) of triangular MF.

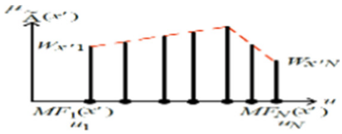

Fig. 6. Secondary membership function for vertical slice at x'.

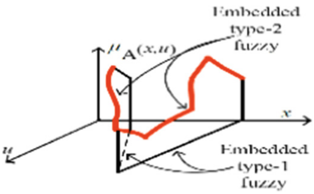

Fig. 7. Embedded of type-1 and -2 fuzzy on 3-dimension MF.

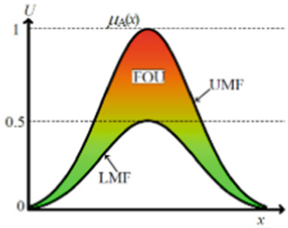

Fig. 8. Area of FOU is located between lower and upper MFs.

seconder MF, so the type-2 fuzzy produces the MF in 3-dimension. Figure 7 shows membership function (MF), where this MF is embedded by type-1 fuzzy on 2-dimension $\left(x, \mu_{\tilde{A}}(x)\right)$ and type-2 fuzzy on 3-dimension $\left(x, u, \mu_{\tilde{A}}(x, u)\right)$. Type-2 fuzzy MF is reduced to Type-1 fuzzy when all uncertainty not exists. When all the uncertainties on the left-and right-end points not exist, then only dashed triangles survive. This similar way occurs on probability theory, when randomness is collapsed to deterministic. Another way to represent the type-2 fuzzy MF is to sketch of foot of uncertainty (FOU) on 2-dimension. To depict of FOU on 2-dimension is shown in Fig. 8.

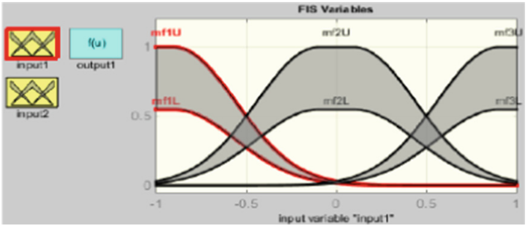

Fig. 9. Gauss-2 membership functions for Input 1 (rotor speed deviation).

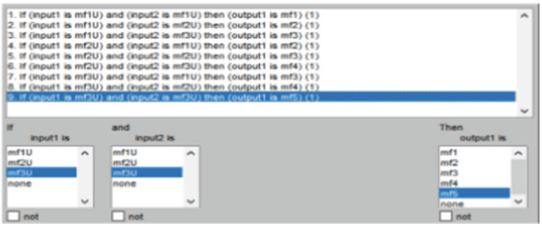

Fig. 10. Rule base of IT2F PSS.

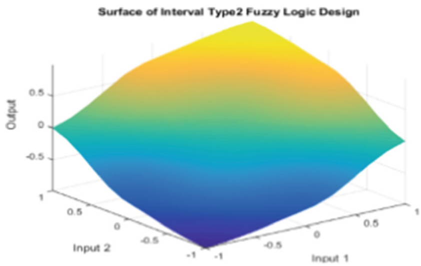

Fig. 11. Control surface of IT2F PSS.

Figure 9 describes the 3 Gauss-2 MF for input 1. Each MF are constructed by lower (mf1L- mf3L) and upper (mf1U- mf3U) MFs. Constanta sets (−1; −0.5; 0; 0.5 and 1) are used as an output membership function. To connect the input-output relationship, 9 rules based are created. The example of rule based: If Input1 is mf1U and Input2 is mf1U then Output1 is mf1. The illustration of rule based is shown in Fig. 10. Control surface is represented by Fig. 11.

4 Simulation Results and Analysis

In this section, we use two examples (single machine connected to infinite bus and 9-bus 3-machine) in order test the ability of the proposed PSS. The simulation is conducted by using Matlab/Simulink 2014b [23] on PC computer.

4.1 IT2F PSS Testing on a Single Machine

The IT2F-PSS is tested on a single machine. The system is assumed operates on normal mode to handle load. At this session, additional electrical load is attached on terminal generator. Meanwhile, the mechanical force is remaining still not increased. So, it is meaning that the machine deficiency of the mechanical force and the rotor speed is decelerated and the rotor angle is increased at a moment. This mechanism is shown in Fig. 12 for disturbance is implemented by 1% additional load. It is shown that power system without PSS gives the maximum overshoot of rotor speed deviation is -2.45×10^{-4} rad/s. The maximum overshoot of conventional (lead-lag) and IT2F PSSs were -2.03 and -1.02×10^{-4} rad/s, respectively. The settling time is achieved at more than 5 s for system without PSS and conventional PSS. The settling time for IT2F PSS was achieved at 2.34 s. For 5% disturbing, peak overshoot was achieved at -12.14, -10.07 and 9.94×10^{-4} rad/s, for without, conventional and IT2F PSS, respectively. The settling time was more than 5 s for without and conventional PSS. While, settling time for IT2F PSS was at 3.19 s. Performance of rotor speed deviation is listed in Table 1.

Table 2 lists the rotor angle deviation when the disturbing is applied on the system. For 1% disturbing, the peak overshoot of system without PSS, conventional and IT2F PSS were -1.53, -1.26 and $-0.54°$, respectively. The settling time for without and conventional PSS were achieved more than 5 s. The settling time for IT2F PSS was achieved at 4.5 s. Illustration of power angle a single machine is depicted in Fig. 13.

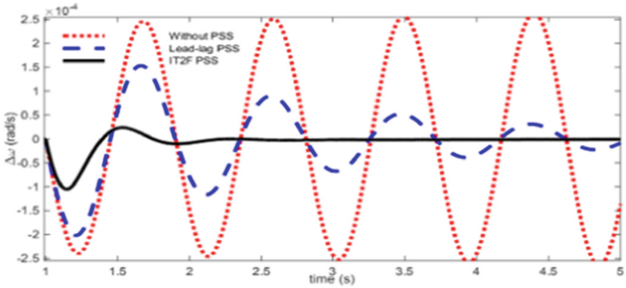

Fig. 12. Performance of IT2F PSS on a single machine.

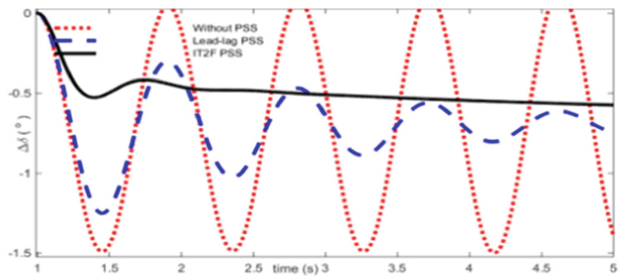

Fig. 13. Deviation of power angle by 1% disturbing on a single machine.

Table 1. Rotor speed deviation of single machine.

Disturbance (%)	Without PSS		Conventional PSS		IT2F PSS	
	$M_p \times (-10^{-4})$ (rad/s)	t_{st} (s)	$M_p \times (-10^{-4})$ (rad/s)	t_{st} (s)	$M_p \times (-10^{-4})$ (rad/s)	t_{st} (s)
1	2.45	>5	2.03	>5	1.02	2.34
5	12.14	>5	10.07	>5	9.94	3.19

Table 2. Rotor angle of single machine.

Disturbance (%)	Without PSS		Conventional PSS		IT2F PSS	
	$M_p \times (-10^{-4})$ (rad/s)	t_{st} (s)	$M_p \times (-10^{-4})$ (rad/s)	t_{st} (s)	$M_p \times (-10^{-4})$ (rad/s)	t_{st} (s)
1	1.53	>5	1.26	>5	0.54	4.5
5	0.131	>5	0.108	>5	0.105	3.02

Moreover, for disturbing is increased into 5%. The peak overshoot was achieved at −0.131, −0.108 and −0.105° for without, conventional and IT2F PSS.

4.2 Performance of IT2F PSS on a 3-Machine System

Performance of interval type-2 fuzzy PSS also tested for multi machine power system. Disturbing is 1% additional load on Machine 2, simulation results are listed on Table 3. The peak overshoot for rotor speed deviation Machine 2 of systems without PSS was achieved at -0.98×10^{-4} rad/s. The settling time was more than 2 s. Meanwhile, when system equipped by the IT2F-PSS rotor speed deviation was achieved at -0.153×10^{-4} rad/s. And, the system was settled at time of 0.19 s.

For Machine 3, the simulation results for rotor speed deviation are as follows: Peak overshoot was achieved at -0.39×10^{-4} rad/s for system without PSS. The system is oscillated and the settling time achieved more than 2 s. Peak overshoot for IT2F-PSS was achieved at the value of -0.21×10^{-4} rad/s. The settling time was achieved at 0.32 s. For the disturbing was increased to 5%, simulation results are as follows: Peak overshoot was achieved at -4.97×10^{-4} rad/s and settling time more than 2 s, for system without PSS. While, for IT2F-PSS the peak overshoot was achieved at -2.36×10^{-4} rad/s and settling time at 0.23 s. The peak overshoot for Machine 3 was achieved at -1.86×10^{-4} rad/s and settling time more than 2 s. The peak overshoot when the system equipped by IT2F-PSS was at -1.52×10^{-4} rad/s and the settling time was at 0.48 s. Moreover, the system without PSS and IT2F-PSS is also evaluated on the rotor angle of Machine 2 and Machine 3. Where, the peak overshoot of the rotor angle Machine 2 was at −0.27° and settling time was more than 2 s. When the disturbing was increased to

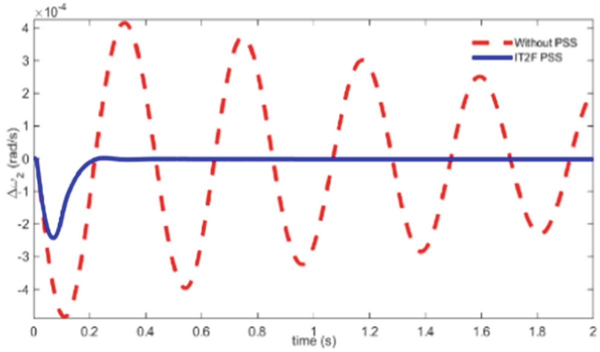

Fig. 14. Improvement of rotor deviation by 5% disturbing on machine 2.

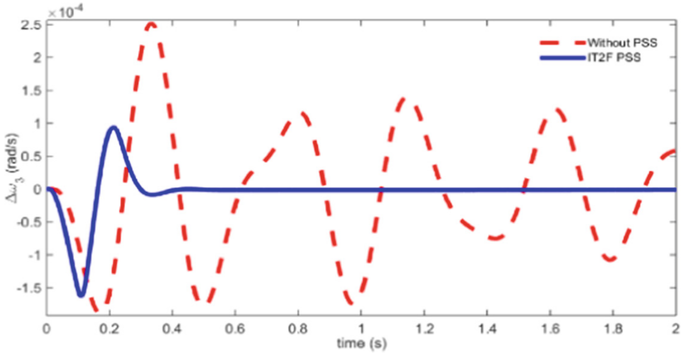

Fig. 15. Rotor deviation machine 2.

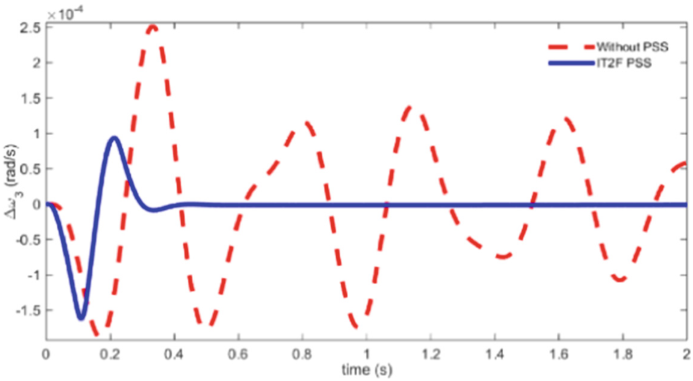

Fig. 16. Response enhancement for $\Delta\omega$ machine 3.

5%, the peak overshoot was at -1.41° and the settling time was more than 2 s. Response for rotor speed of Machine 2 is depicted in Fig. 14.

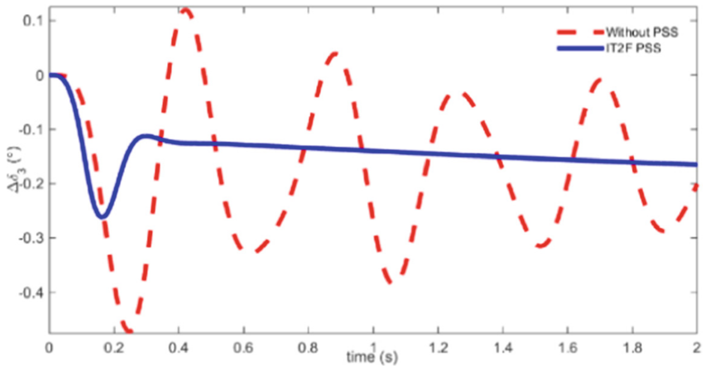

Fig. 17. Power angle of machine 3.

Table 3. Rotor speed deviation of multi machine.

Machine 2				
Disturbance (%)	Without PSS		IT2F PSS	
	$M_p \times (-10^{-4})$(rad/s)	t_{st} (s)	$M_p \times (-10^{-4})$ (rad/s)	t_{st} (s)
1	0.98	>2	0.153	0.19
5	4.97	>2	2.36	0.23
Machine 3				
Disturbance (%)	Without PSS		IT2F PSS	
	$M_p \times (-10^{-4})$(rad/s)	t_{st} (s)	$M_p \times (-10^{-4})$(rad/s)	t_{st} (s)
1	0.39	>2	0.21	0.32
5	1.86	>2	1.52	0.48

Rotor angle for machine 2 is illustrated in Fig. 15. The system equipped by IT2F-PSS, the peak overshoot of rotor angle Machine 2 was at −0.025° and settling time was at 0.17 s. For the disturbing was increased to 5%, the peak overshoot of rotor angle Machine 2 was at −0.51° and settling time was at 0.2 s. Simulation results of rotor angle for Machine 3 are as follows: Peak overshoot was at −0.095° and settling time was more than 2 s for system without PSS. The peak overshoot was at −0.024° and settling time was at 0.31 s for system equipped by IT2F-PSS. For disturbing at 5%, the rotor angle achieved peak overshoot at −0.48° and settling time was more than 2 s for system without PSS. While, the rotor angle achieved peak overshoot at − 0.26° and settling time was at 0.36 s for system with IT2F-PSS. Rotor speed and angle for machine 3 are illustrated in Figs. 16 and 17, respectively.

Table 4. Rotor angle deviation of multi machine.

Machine 2				
Disturbance (%)	Without PSS		IT2F PSS	
	$M_p \times (-10^{-4})$(rad/s)	t_{st} (s)	$M_p \times (-10^{-4})$ (rad/s)	t_{st} (s)
1	0.27	>2	0.025	0.17
5	1.41	>2	0.51	0.20
Machine 3				
Disturbance (%)	Without PSS		IT2F PSS	
	$M_p \times (-10^{-4})$(rad/s)	t_{st} (s)	$M_p \times (-10^{-4})$(rad/s)	t_{st} (s)
1	0.095	>2	0.024	0.31
5	0.48	>2	0.26	0.36

5 Conclusion

Load and generation on power are not constant at all time, but there are always changes according to consumers need. Rotor oscillation occurs in power system due to energy balance on mechanical-electrical relationship is disturbed in generator system. To damp the rotor oscillation problem, power system stabilizer (PSS) is one common method to apply. However, conventional PSS gives not good oscillation. In this research, interval type-2 fuzzy (IT2F)-PSS is proposed to reduce the rotor oscillation. The performance of the PSS is assessed by peak overshoot and settling time of rotor speed deviation and rotor angle. The peak overshoot is achieved at -2.45 and -2.03×10^{-4} rad/s for without and conventional PSS. While, the peak overshoot is achieved at -1.02×10^{-4} rad/s for IT2F-PSS. Settling time is more than 5 s for without and conventional PSS. The IT2F-PSS gives settling time at 2.34 s. By this simulation it is show that the IT2F-PSS gives better performance compared to other PSS. Future work is to peak overshoot and settling time reduction using artificial intelligent optimizing method on PSS parameters.

Acknowledgment. The authors would like thank to Direktorat Jenderal Pendidikan Tinggi, Riset dan Teknologi, Kementerian Pendidikan Tinggi, Kebudayaan, Riset dan Teknologi RI for financial support of this research through PDKN research 2022 scheme.

References

1. Shi, A. *et al.*: Convolutional neural network-based power system transient stability assessment and instability mode prediction, Appl. Energy 263 (2019).
2. Kamwa, R., Grondin, S., Trudel, G., Ieee, A.: IEEE PSS2B versus PSS2B: The limit of performance of modern power system stabilizer, IEEE 20(2), pp. 903–915 (2005).
3. Sharma, K. K., et al.: Power quality and transient analysis for a utility-tied interfaced distributed hybrid wind-hydro controls renewable energy generation system using generic and multiband power system stabilizers, Energy Reports 7, pp. 5034–5044 (2021).

4. Hadap A., Vaishnav, S.: H-robust technique based ant optimal power system for solar energy power system stabilizer, Mater. Today Proc. 51, pp. 118–124 (2021).
5. Ray, P.K., Paital, S.R., Mohanty, A., Eddy, F.Y.S., Gooi, H.B.: A robust power system stabilizer for enhancement of stability in power system using adaptive fuzzy sliding mode control, Appl. Soft Comput. J. 73, pp. 471–481 (2018).
6. Hossein-Zadeh, N., Kalam, A.: An indirect adaptive fuzzy-logic power system stabiliser, Int. J. Electr. Power Energy Syst. 24(10) pp. 837–842 (2002).
7. Rao, P.S., Sen, I.: Robust pole placement stabilizer design using linear matrix inequalities, IEEE Transc. Power System 15(1) pp. 313-319 (2000).
8. Bevrani, H. Hiyama, T. Bevrani, H.: Robust PID based power system stabiliser: Design and real-time implementation, *Int. J. Electr. Power Energy Syst.*, 33(2) pp. 179–188 (2011).
9. Talaq, J., Optimal power system stabilizers for multi machine systems, *Int. J. Electr. Power Energy Syst.*, 43(1) pp. 793–803 (2012).
10. Peres, W., Silva, Jr.I.C., Passos Filho, J.A.: Gradient based hybrid metaheuristics for robust tuning of power system stabilizers, *Int. J. Electr. Power Energy Syst.* 95, pp. 47–72 (2018).
11. Shabani, H.R., Kalantar, M., Hajizadeh, A.: Real-time transient instability detection in the power system with high DFIG-wind turbine penetration via transient energy, *IEEE Syst. J.*, pp. 1–12 (2021).
12. Ginarsa, I.M., Soeprijanto, A., Purnomo, M.H.: Controlling chaos and voltage collapse using an ANFIS-based composite controller-static var compensator in power systems, Int. J. Electr. Power Energy Syst. (2013).
13. Ginarsa, I.M., Nrartha, I.M.A., Muljono, A.B., Ardana, I.P.: ANFIS-based controller Application to regulate firing angle of inverter in average value model-high voltage direct current transmission system, ICGTEIS Conf. Bali, pp. 1–6 (2018).
14. Sae-Kok, W., Yokoyama, A., Verma, S.C., Ogawa, S.: Excitation control system design of rotary type frequency converter for performance improvement of power system dynamics, IEEE Trans. Energy Convers. 21(1) pp. 210–220 (2006).
15. Ginarsa, I.M., Nrartha, I.M.A., Muljono, A.B., Zebua O.: Desain power system stabilizer berbasis fuzzy fipe-2 untuk perbaikan stabilitas mesin tunggal, *J. Rekayasa Elektr.*, 14(1) pp. 1–8 (2018).
16. Ray, P. K., *et al.*: A hybrid firefly-swarm optimized fractional order interval type-2 fuzzy PID-PSS for transient stability improvement, *IEEE Trans. Ind. Appl.* (2019).
17. Muljono, A.B., Ginarsa, I.M., Nrartha, I.M.A., Dharma, A.: Coordination of adaptive neuro fuzzy inference system (ANFIS) and type-2 fuzzy logic system-power system stabilizer (T2FLS-PSS) to improve a large-scale power system stability, *Int. J. Electr. Comput. Eng.* (2018).
18. Nrartha, I.M.A., Ginarsa, I.M., Muljono, A.B.: Aplikasi fuzzy type-2 PSS untuk perbaikan stabilitas dinamik pembangkit listrik tenaga mikro hidro dan diesel, Jurnal JSTL 7(2) pp. 185–194 (2021).
19. Sreedivya, K.M., Jeyanthy, P.A., Devaraj, D.: Improved design of interval type-2 fuzzy based wide area power system stabilizer for inter-area oscillation damping, *Microprocess. Microsyst.* 83, p. 103957 (2021),
20. Kundur, P.: Power system stability and control, McGraw-Hill (1994).
21. Ekinci, S., Zeynelgil, H.L., Demiroren, A.: A didactic procedure for transient stability simulation of a multi-machine power system utilizing SIMULINK, Int. J. Electr. Eng. Educ. 53(1) pp. 54–71 (2016).
22. Zhou, H., Ying, H., Zhang, C.: Effects of increasing the footprints of uncertainty on analytical structure of the classes of interval type-2 Mamdani and TS fuzzy controllers, *IEEE Trans. Fuzzy Syst.* 27(9) pp. 1881–1890 (2019).
23. Matlab: Matlab Simulink. The Mathworks, Old Baltimore Pike, Beltsville (2014).