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Electrical Systems "Special issue AMPE2015" SELECTED PAPER Power System Stabilizer Based on Interval Type 2 Fuzzy Sliding Mode Controller for Oscillation Damping on 500kV Java-Bali Electrical Power System JES Journal of Journal of Journal of Journal of Electrical Electrical Electrical Electrical Systems Systems Systems Systems This paper proposed a new method to design a power system stabilizer (PSS). The proposed method based on type 2 fuzzy logic sliding mode controller (IT2FSMC). IT2FSMC is a combination of interval type 2 fuzzy logic controller (IT2FLC ) and the sliding mode controller (SMC). Java-Bali 500 kV transmission system used as a test system to evaluate the performance of the proposed method.

A new model for interconnection between generator systems also introduced in this paper. The performance of the PSS resulted from proposed method is compared with fuzzy sliding mode controller (FSMC). Results show that the proposed method is more effective than FSMC to improve system performance through a minimum settling time of PSS. This scheme provides a new procedure in designing power system stabilizer (PSS) to improve power system stability performance. Keywords: Power System Stabilizer; Interval Type 2 Fuzzy Logic Sliding Mode Controller. 1. Introduction Nowadays a quick population growth leads a load increment in power systems.

This load increment is not accompanied by the addition of transmission lines and generation. This happens due to limited availability of resources and the environmental constraints are very tight, resulting power system more burdened than before and the electrical power system operated at its stability limit. It also causes the damping oscillations in power systems become not optimal [1].

The recent research regarding **the power system stability** shown that an additional control signal given to the excitation system and/ or governor system of a generator can be used **to damp the oscillations and** improve the dynamic performance of power system [2]. **Power system stabilizer (PSS)** provides additional signal control in **the excitation system to** dampen the oscillations and **improve the stability of the power system**. This strategy is the simplest, economical and flexible to **improve the stability of the power** system.

Some signals used for PSS input are terminal voltage deviation, frequency deviation, power acceleration, electric power from generator and their combination are presented in [3]. In general, PSS **designed based on a transfer function of a** linear generator model at a certain operating point [4]. Such standard PSS which is designed for a particular operating point with linear transfer function model **do not have a** good performance in reducing oscillations that occur for a variety range of operating conditions that exist in the power system.

Recently many new control method **based on the artificial** intelligence have been proposed for designing adaptive PSS **such as fuzzy logic controller (FLC)** [5-7], **neural International Conference on Advanced Mechanics, Power and Energy 2015 (AMPE2015), 5-6 December 2015, Kuala Lumpur, Malaysia 2 network (NN)** [8] **and a genetic algorithm (GA)** [9] and the results are very satisfying. Fuzzy logic controller (FLC) is a simple controller, its structure consists of fuzzification, fuzzy rules and defuzzification. FLC has been widely **used in various applications** to solve complex problems that cannot be solved using conventional mathematical techniques [10]. Generally, the operation used in the FLC is the error input variable and error change.

This causes a large **number of fuzzy rules** required and makes the analytical process becomes very complex. To reduce the number of error input variables and error change in the fuzzy rules, it is required to combine FLC with sliding-mode control method. It is called **fuzzy sliding mode control (FSMC)** [11-13]. By combining these two methods, only sliding surface variable is needed as fuzzy variable input in the fuzzy rules. The main advantage of the FSMC is less **the number of fuzzy rules** than using FLC. In addition, the use of sliding mode control can improve the performance of the system **against**

parameter variations and external disturbances [14].

FLC and FSMC design requires experience and knowledge to designing the membership functions and fuzzy rules because the degree of membership FLC and FSMC is crisp numbers in the interval [0, 1]. Then it cannot directly deal the uncertainty. In addition, for real-time applications the words used in the fuzzy rules can be different for different operators. This leads to uncertainty rules with the information available. To resolve this problem, Zadeh [15] proposed the concept of type-2 fuzzy system that is an extension of type-1 fuzzy system. A type-2 fuzzy used if-then rules also, but the membership function is the set of type-2 fuzzy.

A type-2 fuzzy system characterized by fuzzy membership functions, namely the degree of membership for each element is a fuzzy set in the interval [0, 1], unlike the system of type-1 fuzzy system with a degree of membership is crisp numbers in the interval [0,1 ]. Thus, type-2 fuzzy particularly useful in circumstances when the degree of membership is very difficult to determine with precision. This paper proposes a new method to design a power system stabilizer (PSS). The proposed PSS method based on type 2 fuzzy logic sliding mode controller (IT2FSMC). IT2FSMC is a combination of interval type 2 fuzzy logic controller (IT2FLC) and the sliding mode controller (SMC) combine the advantages of each methods.

This controller can provide robustness more than conventional FLC method to handle the uncertainty and disturbance. This paper is organized as follows: Part II presents a brief discussion on the modelling of Java-Bali 500kV power system. Then, Section III describes the proposed method. Part IV is implementation of the proposed method. Chapter V describes the design simulation and the analysis. The last section is the conclusion. 2. Power System Modelling This paper is using Java-Bali 500 kV power system that consists of 8 generators, 30 transmission line with a total number of buses is 25 bus. A simplified Single Line Diagram of the Java-Bali 500 kV is shown in Figure 1.

This simulation use the data on April 19th 2011 at 13:30 pm when the system had peak load with the total load is 10,361 MW and 3,565 MVAR and the generation power is 10635.611 6244.647 MW and MVAR. Power generation, load, and transmission line data were taken from reference [16]-[18] and shown in Table 5 and Table 7 in the Appendix. While the generator data includes the governor, turbine, AVR, are taken from reference [19] and shown in Table 6 in the Appendix. J.

Electrical Systems "Special issue AMPE2015" 3 International Conference on Advanced Mechanics, Power and Energy 2015 (AMPE2015), 5-6 December 2015, Kuala Lumpur, Malaysia 4 1 gu gu gu K Y Y T R T ? ? = - ? - ? · ? (1) 1 1 m m tu tu T Y T T T ? = ? - ? ? (2)

$\delta$   $\omega$   $\omega$   $\omega$  =  $\omega$  (3)  $\frac{1}{M} \frac{d^2 \delta}{dt^2} + \frac{D}{M} \frac{d\delta}{dt} - \frac{E' q}{M \omega_s} \sin \delta = -\frac{T_m}{M} - \frac{K_g}{M} \omega$  (4)  $\frac{dV_f}{dt} = -\frac{V_f}{T_{AVR}} + \frac{K_{AVR}}{T_{AVR}} (V_r - V)$  (5)  $\frac{dR}{dt} = -\frac{R}{T_r} + \frac{K_r}{T_r} (V_r - V)$  (6)  $\frac{dY}{dt} = -\frac{Y}{T_g} + \frac{K_g}{T_g} (V_r - V)$  (7) where,  $Y$  = valve position deviation  $T_m$  = mechanical torque deviation  $\delta$  = rotor angle deviation  $\omega$  = frequency/rotor angle speed deviation  $E' q$  = generator internal voltage deviation  $V_f$  = exciter output voltage deviation  $V_r$  = transducer output voltage deviation  $K_g$  = governor gain  $T_g$  = governor response time  $R$  = speed droop  $T_t$  = time constant turbine  $b$  = generator operating speed/frequency  $M$  = generator inertia  $D$  = generator damping  $T'_{d0}$  = generator transient time constant  $K_a$  = AVR gain  $T_a$  = AVR time constant  $T_r$  = transducer time constant Modelling interconnection system for Java-Bali 500 kV power system in Figure 1 into the proposed linear multimesin model from this paper are shown in Figure 3.

Output terminals voltage variable of each generator transforms into joint axis dq model using Equation (8) and Equation (9).  $V_d = V \cos \delta$   $V_q = V \sin \delta$  Transformation of axis generator terminal voltage variable is obtained using Equation (10).  $V_d = V \cos \delta$   $V_q = V \sin \delta$  (10) After the generator output voltage in the dq axis is known, then calculate the current injection of each generator in the dq axis. Injection current value is used to calculate the power injection of each generator. Calculation of current injection is shown in equation (11).

$I_d = \frac{V_d}{Z} \cos \delta$   $I_q = \frac{V_q}{Z} \sin \delta$  (11) where, RED = reduced transmission admittance matrix dq  $DQ = \frac{1}{Z} \begin{bmatrix} \cos \delta & \sin \delta \\ -\sin \delta & \cos \delta \end{bmatrix}$   $QD = \frac{1}{Z} \begin{bmatrix} \sin \delta & \cos \delta \\ \cos \delta & -\sin \delta \end{bmatrix}$   $DQ = \frac{1}{Z} \begin{bmatrix} \cos \delta & \sin \delta \\ -\sin \delta & \cos \delta \end{bmatrix}$   $QD = \frac{1}{Z} \begin{bmatrix} \sin \delta & \cos \delta \\ \cos \delta & -\sin \delta \end{bmatrix}$   $P = \frac{1}{Z} \begin{bmatrix} \cos \delta & \sin \delta \\ -\sin \delta & \cos \delta \end{bmatrix}$   $V = \begin{bmatrix} V_d \\ V_q \end{bmatrix}$   $I = \begin{bmatrix} I_d \\ I_q \end{bmatrix}$  Figure 3. Linear Model of Java-Bali 500 kV power system [19] Injection power of each generator to the transmission line returns into each generator. So the overall model is formed into a closed loop system.

Rated power injection of each generator is obtained using equation (13) - equation (16) after reverse transformation a current and voltage variable into axis d and q generator using equation (12).  $P = V_d I_d + V_q I_q$  (12)  $P = V_d I_d + V_q I_q$  (13)  $P = V_d I_d + V_q I_q$  (14)  $P = V_d I_d + V_q I_q$  (15)  $P = V_d I_d + V_q I_q$  (16)

International Conference on Advanced Mechanics, Power and Energy 2015 (AMPE2015), 5-6 December 2015, Kuala Lumpur, Malaysia 6 3. Proposed Method Sliding surface plays a very important role in the design IT2FSMC.

It can dominate the dynamic behavior of the control system as well as reducing the size of the basic rules of fuzzy (fuzzy rule base). Sliding surface is chosen as input variables of the fuzzy inference rules. So the number of fuzzy rules is fewer than variable state error ( $e$ ) and input variables ( $s$ ) as input variables shown in equation (17).  $s + e = e$  (17) where,  $i_{ref} - i = e$  (18)  $(1) e e t e t = - - ?$  (19)  $0 ? >$  is positive constant. In terms of determining the magnitude of the control signal, design of IT2FSMC controller is simpler than SMC. It is because magnitude of the IT2FSMC control signal obtained from the fuzzy rules. For example there are number of  $n$  fuzzy rules.

Each rule follows this form: Rule 1: if  $s$  is NB then control signal is NB Rule 2: if  $s$  is NM then control signal is NM ... Rule  $n$ : if  $s$  is PB then control signal is PB Block diagram of PSS-based IT2FSMC that installed on each generator of Java-Bali 500kV power system is shown in figure 4 below.  $s + e = e$  PSS  $i V - ?$  Out  $i K -$  Inp  $i K -$  ref  $i ? - ? i ? ?$  Figure 4. Block diagram of PSS-Based IT2FSMC While block diagram of PSS-based IT2FSMC that used as an additional control signal for excitation system are shown in Figure 5.

$1 1 r sT + ? t V f V \max V \min V \text{ref } V s + e = e$  PSS  $V ?$  Out  $K$  Inp  $K \text{ref } ? ? ? ?$  Figure 5. Block diagram of generator excitation system with the additional of signal PSS-based IT2FSMC Membership functions and fuzzy rules are the basic criterion to determine the performance of IT2FSMC. It is very important to define the fuzzy rules in the design of IT2FSMC which is suitable with the characteristics of the control system in order to achieve optimal performance.

The membership function input and output variables of IT-based PSS 2 SMC as sliding surface ( $s$ ) and additional control signals PSS  $V ?$  injected into the excitation system of each generator are shown in figure 6. In the simulation PSS is installed on all generator, but in this paper only shows the membership function and the generator response only for J. Electrical Systems "Special issue AMPE2015" 7 Suralaya generator because it is the slack generator of the Java Bali 500 kV power system.

In this paper, the type of fuzzy membership function used is a triangular membership form because this type are very economical, simple and efficient. IT2FSMC input membership function of Suralaya generator IT2FSMC output membership function of Suralaya generator Figure 6. IT2FSMC-based PSS membership function for Suralaya generator Fuzzy rules for PSS based IT2FSMC are identical to the rules-based PSS FSMC. The basic rules that is used consist of seven rules framed by the if-then rules.

The fuzzy rules are summarized in Table 1 built using the basic idea. If the state far from the sliding surface it need substantial control effort to the system. Otherwise if the state near sliding surface, it only need small control efforts to the system. Therefore, the state

can quickly reach the sliding surface without large overshoot. Based on this state of control, desired output can be achieved and the system remains in a stable state. Table 1. Fuzzy rules for IT2FSMC-based PSS s NB NM NS ZE PS PM PB PSS V ? NB NM NS ZE PS PM PB Scale factor value for PSS based FSMC and IT2FSMC are shown in table 2. While the value of ? used for PSS based FSMC and IT2FSMC is 5. Table 2.

Scale factor of PSS based IT2FSMC for each generator Generator FSMC IT2FSMC Kinp Kout Kinp Kout Suralaya 0.1 0.75 0.1 0.75 Muaratawar 0.1 3.75 0.1 3.75 Cirata 0.5 7.5 0.5 7.5 Saguling 0.5 2.5 0.5 2.5 Tanjungjati 0.5 7.5 0.5 7.5 Gresik 0.1 2.15 0.1 2.15 Paiton 0.5 7.15 0.5 7.15 Grati 0.45 3.5 0.45 3.5 4. Purposed Method Implementation International Conference on Advanced Mechanics, Power and Energy 2015 (AMPE2015), 5-6 December 2015, Kuala Lumpur, Malaysia 8 To illustrate the effectiveness of the proposed model we have presented illustrative case study.

The model has been implemented and solved with the commercial optimization package MOSEK Solver Engine – Premium Solver Platform, version 6.0, Frontline System, Inc., on 3.0 GHz PC with 1 GB of RAM. Step by step designing PSS based IT2FSMC given as follows: 1. Input the generators, transmission line and load data 2. Run Load Flow 3. Perform transmission admittance matrix reduction 4. Apply PSS based IT2FSMC 5. Design IT2FSMC membership functions using trial and error method (TEM) 6. Calculate Integral of Time Multiply by Absolute Error (ITAE) value 7.

If the ITAE value not minimum as the expected value then go to number 4, if the ITAE value as expected then go to number 8 8. Finish simulation Integral of Time Multiply by Absolute Error (ITAE) is an index of the performance criterion commonly used in cthe design of control. In this research, time domain ITAE performance index criterion are suggested to evaluate the proposed method. ITAE performance index criteria defined in Equation (20).

0 0 ( ) ( ) sim sim i e t i ref i i t t ITAE t dt t dt t t ? = - - = ?y? (20) Where sim is integration time in simulation. In this research ITAE value is the sum of the calculation ITAE of each generator defined in Equation (21). 1 1 0 0 ( ) ( ) t t N N sim sim i ref i i i t t t e t dt t dt ITAE ? ? - = = ?y? = - ?y? = (21) Where i=1,..., N ; N is total generation in Java Bali 500 kV power system 5. Simulation and Analysis Simulation and analysis are discussed in this section. Simulations performed uses a PC Pentium Intel (R) Core (TM) i3-2370M CPU @ 2:40 GHz 2:00 GB RAM. The main objective of the simulation is to evaluate the performance and accuracy of the proposed method. This simulation using MATLAB software.

Java-Bali 500kV power system give a small signal interference of 0.05 P.U on all

generators to evaluate and validate the robustness of the proposed method. At Suralaya generator there is an improved response of frequency deviation. Frequency deviation response on Suralaya generator is shown in figure 7. From the figure can be understood that the system response of the Suralaya generator using PSS based IT2FSMC is stable more quickly and able to suppress overshoot compared to PSS based FSMC. J.

Electrical Systems "Special issue AMPE2015" 9 Frequency deviation (P.U) Figure 7. Frequency deviation response on Suralaya generator Table 3 shows a comparison of the overshoot and settling time value for each method. From the table it can be seen that PSS based IT2FSMC have the most minimum overshoot value and have the fastest settling time. This indicates that the PSS based IT2FSMC improving the performance on a system better than PSS based FSMC. Table 3. Overshoot dan settling time of frequency deviation response on Suralaya generator overshoot Settlingtime without PSS -0.0005024 8.521 FSMCPSS -0.0005024 8.313 IT2FSMCPSS -0.0004575 4.101 Table 4 shows the comparison of the ITAE value for all generator in the Java Bali 500 kV power system. From table can be understood that the ITAE value from PSS based IT2FSMC is 2.9415 and it is the most minimum value compared with PSS based FSMC and without PSS.

Result of the frequency deviation Suralaya generator in figure 7; overshoot and settling time Suralaya generator in table 3; ITAE value in the table 4 shows that PSS based IT2FSMC have the most minimum overshoot, fastest settling time dan the most minimum ITAE value. This indicates that the PSS-based IT2FSMC can improve the performance of dynamic stability of the Java Bali 500 kV power system better than using PSS based FSMC. Table 4. Comparison of ITAE value ITAE without PSS 8.1413 FSMCPSS 4.7505 IT2FSMCPSS 2.9415 6. Conclusion A new approach to design PSS by using IT2FSMC has been proposed in this paper. Upper and lower limit interval on the set of the IT2FSMC based PSS membership has very important role for PSS based IT2FSMC output.

From the simulation, it can be concluded International Conference on Advanced Mechanics, Power and Energy 2015 (AMPE2015), 5-6 December 2015, Kuala Lumpur, Malaysia 10 that PSS-based IT2FSMC can improve the performance of dynamic stability of Java Bali 500 kV power system better than using PSS based FSMC. For further development, in order to optimize the PSS based IT2FSMC it requires a membership functions optimization using metaheuristic / artificial intelligence based method. APPENDIS Table 5. Java-bali 500kV load and generation data [16]-[18]

No	Bus	Bus Name	Bus Type	Load	Generation	P (MW)	Q (MVAr)	P (MW)	Q (MVAr)
1	Suralaya	Swing	219	67	3.211,6	1074.1			

2 Cilegon Load 333 179 0 0 3 Kembangan Load 202 39 0 0 4 Gandul Load 814 171 0 0 5  
 Cibinong Load 638 336 0 0 6 Cawang Load 720 217 0 0 7 Bekasi Load 1126 331 0 0 8  
 Muara Tawar Generator 0 0 1.760 645 9 Cibatul Load 1152 345 0 0 10 Cirata Generator  
 597 201 948 200 11 Saguling Generator 0 0 698,4 150 12 Bandung Selatan Load 477 254  
 0 0 13 Mandiracan Load 293 65 0 0 14 Ungaran Load 193 118 0 0 15 Tanjung Jati  
 Generator 0 0 1321,6 90.0 16 Surabaya Barat Load 508 265 0 0 17 Gresik Generator 127  
 92 900,0 366.3 18 Depok Load 342 95 0 0 19 Tasikmalaya Load 133 33 0 0 20 Pedan  
 Load 365 101 0 0 21 Kediri Load 498 124 0 0 22 Paiton Generator 448 55 3180 917.3

23 Grati Generator 180 132 398,6 100.0 24 Balaraja Load 732 287 0 0 25 Ngimbang Load  
 264 58 0 0 Table 6. Java-bali 500kV generator data [19] Generator Xd Xd' Xq Xq' H Kg Tg  
 KA TA Tdo ' (pu) (pu) (pu) (pu) (pu) (pu) (pu) (pu) (pu) (pu) Suralaya 2.23 0.3 2.19 0.49 5.5  
 20 1 400 0.05 9.4 Muaratawar 2.23 0.3 2.19 0.49 3.5 20 1 100 0.02 9.4 Cirata 2.23 0.3 2.19  
 0.49 3.5 18 2 100 0.04 9.9 Saguling 2.23 0.3 2.19 0.49 3.5 18 2 100 0.02 8 Tanjungjati 2.23  
 0.3 2.19 0.49 5.5 20 1 100 0.05 4.6 Gresik 2.23 0.3 2.19 0.49 5.5 20 1 300 0.04 9.5 Paiton  
 2.23 0.3 2.19 0.49 5.5 20 1 400 0.05 7.9 Grati 2.23 0.25 2.19 0.49 3.5 20 1 100 0.04 9.5  
 Table 7. Java-bali 500kV transmission line data [16]-[18] No. Line R (p.u.) X (p.u.) ½ B  
 (p.u.) 1 1 2 0.000626496 0.007008768 0 2 1 24 0.003677677 0.035333317 0 3 2 5  
 0.013133324 0.146925792 0.003530571 4 3 4 0.001513179 0.016928308 0 5 4 18  
 0.000694176 0.006669298 0 6 5 7 0.004441880 0.042675400 0 7 5 8 0.006211600  
 0.059678000 0 8 5 11 0.004111380 0.045995040 0.004420973 9 6 7 0.001973648  
 0.018961840 0 10 6 8 0.005625600 0.054048000 0 11 8 9 0.002822059 0.027112954 0 12  
 9 10 0.002739960 0.026324191

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