TELKOMNIKA Indonesian Journal of Electrical Engineering
Vol. 14, No. 3, June 2015, pp. 363 ∼ 375
DOI: 10.11591/telkomnika.v12.i9.4678

Fuzzy Logic PSS Assisted by Neighboring Signals to Mitigate the Electromechanical Wave Propagation in Power Systems

Mahmoud N. Ali*
Faculty of Engineering, Shoubra, Benha University
108 Shoubra st., Cairo, Egypt.
* e-mail: mahmoud.nour@feng.bu.edu.eg

Abstract

This paper deals with the mitigation of electromechanical wave propagation in power systems. Different conventional controllers addressed this problem, such as the conventional PSS and the conventional fuzzy logic PSS. In this paper, the fuzzy logic PSS is assisted by auxiliary signals from the fuzzy logic PSS of the interconnected machines to augment the damping of electromechanical wave propagation and the associated oscillations. The neighboring machines speed deviation and its derivatives signals are exploited through the fuzzy logic PSS to assist the local fuzzy logic PSS. The disturbance propagation and reflection phenomena are considered in the design of the adopted strategy. The efficacy of the proposed assistance of the conventional fuzzy logic PSS are examined through different simulation results.

Keywords: *Electromechanical wave propagation, fuzzy logic PSS, interconnected machines*

1. Introduction

Power systems are continually subjected to different contingencies and random events. The power balance between generation and loads is essential to get a stable operation of a power system. The mismatch between the generator mechanical and electrical power forces the generator rotor to deviate from the synchronous reference frame. This electromechanical disturbance propagates through the entire network as an electromechanical wave with a certain speed of propagation [1] [2]. Simulation results [3] [4] and experimental observations [5] emphasized this phenomenon, where its speed of propagation depends on the generators and transmission system parameters [2].

The propagation of the electromechanical wave stresses different equipments in power systems, e.g. generators and transformers. The protection systems may be subjected to a temporary violation of their limits which may cause unexpected generator and/or transmission line tripping, and consequently, the cascading failure occurs [6].

Preventive and emergency control strategies were used to avoid the drawbacks of the electromechanical wave propagation [7] [8]. The preventive control strategies urge to operate the system with high security margins to decrease the possibility of generator tripping. The emergency control strategies take the suitable actions in case of sensing the initiation of a disturbance to lessen the potential effect of its propagation [8].

The conventional power system stabilizer (PSS) has been used many years ago to dampen electromechanical oscillations in power systems. It acts through the excitation system in such a way that the speed deviation generates a component of electrical torque to assist the damping torque, where the lack of sufficient damping torque results in oscillatory instability [9]. PSS is also used to mitigate the spatial propagation of the electromechanical disturbance in power systems [10].

Based on wide area measurements (WAM), some improvements of the conventional PSS were proposed through centralized and decentralized strategies to mitigate the electromechanical

Received February 19, 2015; Revised May 1, 2015; Accepted May 14, 2015

disturbance propagation in power systems [11] [12]. The conventional fuzzy logic power system stabilizer (FLPSS) was effectively employed to extinguish the propagated electromechanical disturbance in power systems [12].

In [13], a zero reflection controller strategy to quench the propagation of electromechanical disturbance was proposed. The strategy in [13] was analogous to the impedance matching to inhibit reflection of traveling electromagnetic waves in transmission lines.

As the disturbance occurs at any place of the system tends to propagate to the entire system and tends to be reflected upon reaching the system boundaries, the proposed strategy in this paper exploits this nature of the disturbance. As the speed deviation generates a proportional component of electrical torque through the conventional PSS or through the conventional fuzzy logic PSS, the neighboring speed deviation signal could be exploited, through a FLPSS, to generate electrical torque to support damping of the coming and reflected disturbance.

From the viewpoint of disturbance location, the nearest to the first place of disturbance are the foremost machines, and the latest machines are the furthest. Through the FLPSS, the speed deviation signals of the foremost machines can assist the damping of the propagated disturbance in the later machines. With the order reversed, the speed deviation signals of the latest machines also can assist the foremost machines, through the FLPSS, to attenuate the reflected disturbance.

The paper is organized as follows. Section 2. introduces the system modeling and formalization of the problem of electromechanical wave propagation. Section 3. demonstrates the proposed strategy to improve the mitigation of electromechanical wave propagation. Section 4. presents a performance evaluation of the proposed strategy. Finally, Section 5. concludes. The appendix presents the parameters of the benchmark power system used in the simulations.

2. System modeling and problem formalization

This section introduces the detailed generator modeling and the fuzzy logic based power system stabilizer control. Some drawbacks of the the problem of electromechanical wave propagation are explained.

2.1. Generator modeling

Different models can represent synchronous machines depending on the degree of details [9] [14]. The adopted detailed model are represented by the following dynamic equations [14]:

$$\dot{E_q'} = \frac{1}{T_{d0}'}(-E_q' + (x_d - x_d')i_d + E_{fd}) \tag{1}$$

$$\dot{E_d'} = \frac{1}{T_{q0}'}(-E_d' - (x_q - x_q')i_q) \tag{2}$$

$$\dot{\delta} = \omega_0 \Delta\omega \tag{3}$$

$$\dot{\Delta\omega} = \frac{1}{2H}(T_m - T_e - D\Delta\omega) \tag{4}$$

$$T_e = E_d' i_d + E_q' i_q + (x_d' - x_q')i_d i_q \tag{5}$$

$$i_q = \Re e\{\frac{1}{r_a + jx'}[(E_q' + jE_d') - (v_q + jv_d)]\} \tag{6}$$

$$i_d = \Im m\{\frac{1}{r_a + jx'}[(E_q' + jE_d') - (v_q + jv_d)]\} \tag{7}$$

where E_q' is the q-axis internal voltage in pu, $E_d{}'$ is the d-axis internal voltage in pu, v_q is the q-axis terminal voltage in pu, v_d is the d-axis terminal voltage in pu, i_q is the q-axis current in pu, i_d is the d-axis current in pu, T_m is the mechanical torque in pu, T_e is the electrical torque in pu, E_{fd} is the field voltage in pu, δ is the rotor angle in rad, $\Delta\omega$ is the speed deviation in pu, ω_0 is the rotor rated angular speed in rad/s, x_d' is the d-axis transient reactance in pu, x'=x_d'=x_q', x_d is the d-axis synchronous reactance in pu, x_q' is the q-axis transient reactance in pu, x_q is the q-axis synchronous reactance in pu, r_a is the generator internal resistance in pu, $T_{d0}^{'}$ is the open circuit d-axis time constant in s, $T_{q0}^{'}$ is the open circuit q-axis time constant in s and D is the damping constant in pu.

2.2. Generator control and fuzzy logic PSS

To counteract the rotor angle and speed deviations, induced from the generator power imbalance, two principal controls have been evolved for synchronous generators, which are the prime mover control and excitation control. The mathematical models of these controllers can be found in [9] [14].

Conventionally, PSS is added to the excitation system to dampen power system oscillations. A fine tuning of PSS parameters gives a satisfactory attenuation of the electromechanical disturbance propagation in power systems [10] [12]. Fuzzy logic power system stabilizer can replace the conventional PSS and can provide more satisfactory damping for different modes of electromechanical oscillations [15] [16] and for the disturbance propagation in power systems [12].

The conventional PSS employs fixed parameter model based on system linearization or optimization methods. Such a fixed-parameter PSS is widely used in power systems and has made a great contribution in enhancing power system dynamics [17]. As power systems are dynamic systems and their operation is of a stochastic nature, the conventional fixed-parameter PSS can be replaced by a fuzzy logic based PSS [18].

Fuzzy logic is considered as a powerful tool in encountering challenging problems in power systems because of its capability to handle imprecise, vague or 'fuzzy' information [19]. Fuzzy logic implements human experiences and preferences with the adjustment of membership functions and fuzzy rules. Fuzzy membership functions can have different shapes, e.g., triangular, trapezoidal or Gaussian, depending on the preference and/or the experience of the designer. The fuzzy rules, which describe relationships in a linguistic sense, are typically written as antecedent consequent pairs of (IF-THEN) statements.

A block diagram of a fuzzy controller is shown in Figure 1 [20], in which the input and the output of the fuzzy controller are crisp. The fuzzification process converts each piece of input data to degrees of membership. The rule base introduces the designer's experience in linguistic relationships. In the inference engine, the application of an implication method and the aggregation of all outputs, related to the fuzzy rules, are performed to get the output fuzzy set. The resulting fuzzy set must be converted to a number that can be sent to the process as a control signal, which is called the defuzzification operation. All the processes in the dashed box (see Figure 1) are called fuzzy inference system [21] [22].

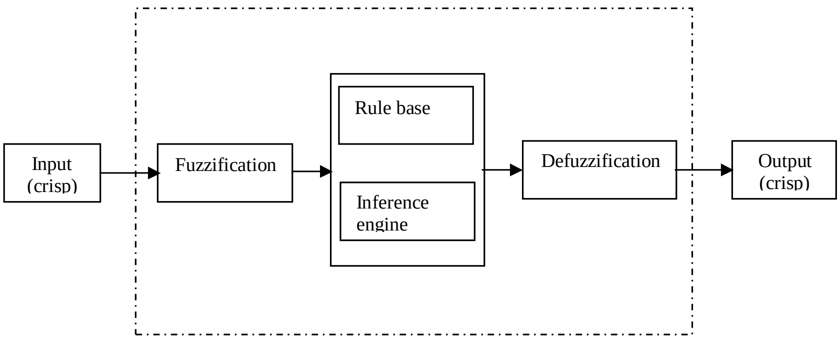

Figure 1. Block diagram of a fuzzy controller.

Empirical knowledge and engineering intuition play an important role in choosing the linguistic variables and their membership functions. Based on the previous experiences introduced in [23] [24] [18], the input signals are chosen as speed deviation ($\Delta\omega$) and its derivative ($\Delta\dot{\omega}$) and the output signal (ΔV_{flpss}) is added to the excitation system reference voltage. The speed deviation derivative ($\Delta\dot{\omega}$) can be calculated from the following relation [23]:

$$\Delta\dot{\omega} = \frac{\Delta\omega_{n+1} - \Delta\omega_n}{\Delta t} \quad (8)$$

where $\Delta\omega_n$ is the speed deviation at step n, $\Delta\omega_{n+1}$ is the speed deviation at step $n+1$ and Δt is time of step of integration.

2.3. The electromechanical wave propagation problems

The phenomenon of electromechanical wave propagation has significant effects on the power systems and their protection systems. As the disturbance propagation imposes a deviation of the generator's rotor angle from its steady-state value, the power transfers in the network is disturbed. The power flow between bus i and bus j in a pure inductive line is given by the following relation:

$$P_{f_{ij}} = P_{max} sin\delta_{ij_0} \quad (9)$$

where $P_{f_{ij}}$ is the power flow between bus i and bus j, δ_{ij_0} is the steady state angle difference and P_{max} is the maximum power transfer, which is given by the following relation:

$$P_{max} = \frac{|V_{g_i}||V_{g_j}|}{X_{ij}} \quad (10)$$

where $|V_{g_i}|$ and $|V_{g_j}|$ are the magnitude of the internal voltage of the two machines i and j and X_{ij} is the reactance of the connecting line. Thus, the deviation in rotor angle results in a change in power transfer, which could be significant and could impact the power system operation [12].

The effects of the electromechanical disturbance propagation on protection systems were presented in [25], where such a propagation often exposes remote relaying systems to false responses. The deviation in the power flow causes a deviation in the current, which affects the operation of the over-current relays and also affects the apparent impedance which, consequently, affects the operation of the distance relays [25]. The propagation of the electromechanical disturbance may trip over-current relays and/or distance relays because of the transient violation of their pick-up settings. This unplanned tripping of protection relays could disconnect one or some components of the power system, which may lead to other disturbances [12].

3. Proposed strategy of assisted FLPSS

In the proposed strategy, the phenomenon of propagation and reflection of electromechanical wave in power systems are exploited. The strategy is based on the injection of the output signal of neighboring FLPSS as extra inputs to the excitation system besides the FLPSS of the local machine to improve the damping of electromechanical wave propagation and the associated oscillations.

More specifically, the excitation system of machine (n) has multi FLPSS signals, which are the local FLPSS signal (ΔV_{flpss_n}) and the FLPSS signals of all electrically connected machines (ΔV_{flpss_m}) weighted by a gain K_m as shown in Figure 2. The same strategy is applied at all other machines.

Basing on the phenomenon of disturbance propagation and its reflection upon reaching system boundaries, this strategy is developed. Suppose that machine n is electrically connected to machine m (which represents one or more machines) and it is firstly subjected to a disturbance. The FLPSS of machine n add extra damping through the excitation system of machine m besides the local FLPSS of this machine to counteract the propagated disturbance. Also, the FLPSS of machine m add extra damping besides the local FLPSS of machine n, through the excitation system, to counteract the reflected disturbance. This inter-assistance between the interconnected machines helps in damping the propagated and the reflected disturbance. Normally, a time delay is implied for the disturbance to reach different machines, where, the foremost affected machines are the nearest to the fault location and the last affected machines are the most far. This can

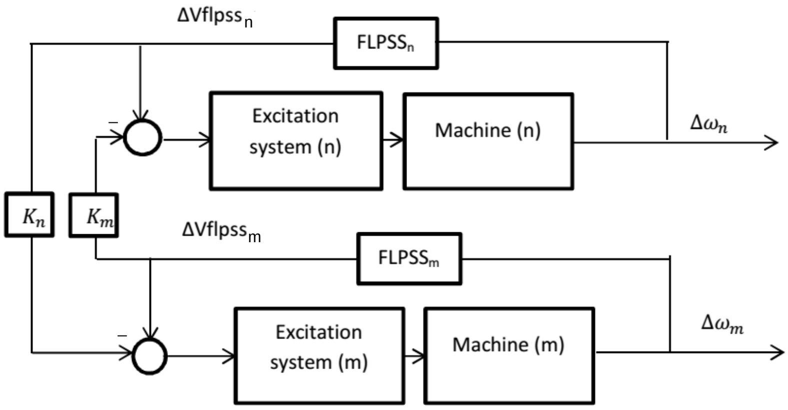

Figure 2. A schematic diagram of the proposed strategy of modifications of the fuzzy logic PSS.

be disregarded for neighboring machines with small electrical distance, where the time delay is small.

To adjust the gains K_n and K_m, an optimization toolbox of MATLAB (FMINCON) is used to minimize an objective function, F_{obj}, which is given as follows:

$$F_{obj} = \sum_{i=1}^{n} \int_{0}^{t_f} (\Delta\omega_i)^2 \, dt \tag{11}$$

where n is the total number of machines in operation and t_f is the period of simulation.

4. Performance evaluation of the proposed strategy

This section presents the performance evaluation of the proposed strategy through the simulation of the uniform two-dimensional (2-D) model [11]. The performance is quantitatively assessed through performance indexes.

4.1. uniform 2-D system

A general regular two-dimension (2-D) grid is shown in Figure 3. It consists of 8×8 nodes, where one generator and a shunt load are connected to each node. The model has identical transmission lines connecting two adjacent nodes Z_{tl}, and identical loads at each node, which is modeled as constant impedance Z_l.

The disturbance is initiated through a sequence of events as follows: Before $t = 0.1\ s$, the system is in steady state. At $t = 0.1\ s$, the generator $(1, 1)$, which has coordinates in the grid $x = 1$, $y = 1$, is lost. The initiated disturbance propagates to the entire network in two dimensions x and y. The propagated disturbance in rotor angle and rotor speed of the 64 generators of the 2-D model are shown in Figures 4 and 5, where all the machines are equipped with the prime mover controller and the excitation system without FLPSS. These Figures show that the disturbance occurs at the first location causes the electromechanical oscillation near this location. It propagates allover the network causing oscillations at each generator and upon reaching boundaries, it is reflected back to the first place causing a new disturbance propagating to the entire network.

4.2. Application of the conventional FLPSS to the uniform 2-D system

For the studied test system, seven linguistic variables are proposed for each input and output variables, which are: LP (large positive), MP (medium positive), SP (small positive), VS (very small), SN (small negative), MN (medium negative) and LN (large negative) [23].

The typical membership functions may be chosen as triangular, trapezoidal, bell shaped, etc. In the simulation of the application of the FLPSS to the 2-D test system, a bell shaped mem-

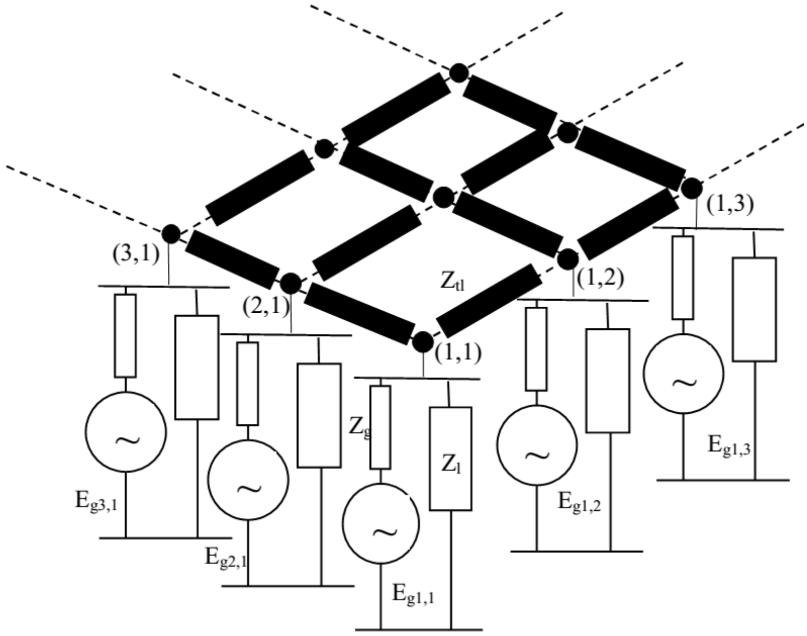

Figure 3. Power system network simulated arranged in a grid of two dimensions.

bership functions are chosen for all the inputs and output variables. The membership functions of the two inputs ($\Delta\omega$ and $\Delta\dot{\omega}$) and the output (ΔV_{flpss}) are shown in Figures 6 and 7, respectively.

A set of rules, which defines the relation between the inputs and the output of the FLPSS is extracted from the previous experience of designing the PSS [18] [23] [24], which are presented in Table 1.

Table 1. Decision table for the output of fuzzy logic PSS.

$\Delta\omega$ \ $\Delta\dot{\omega}$	LN	MN	SN	VS	SP	MP	LP
LP	VS	SP	MP	LP	LP	LP	LP
MP	SN	VS	SP	MP	MP	LP	LP
SP	MN	SN	VS	SP	SP	MP	LP
VS	MN	MN	SN	VS	SP	MP	MP
SN	LN	MN	SN	SN	VS	SP	MP
MN	LN	LN	MN	MN	SN	VS	SP
LN	LN	LN	LN	LN	MN	SN	VS

There are different methods for finding the fuzzy output, e.g., minimum-maximum and maximum-product methods [22] [23]. In these simulations, the minimum-maximum method is adopted. The fuzzy output of each rule is obtained and all outputs are aggregated and defuzzified to get the final output of the FLPSS. There are different techniques for defuzzification of fuzzy quantities such as the maximum method, the height method, and the centroid method, where the later is the most widespread one, and it is adopted in these simulations.

4.3. Application of the proposed strategy to the uniform 2-D system

To evaluate the application of the proposed strategy, the rotor angle and rotor speed deviation responses are examined to evaluate the effectiveness of this strategy.

First, the responses of all rotor angles, referred to the angle of machine (8,8), and rotor

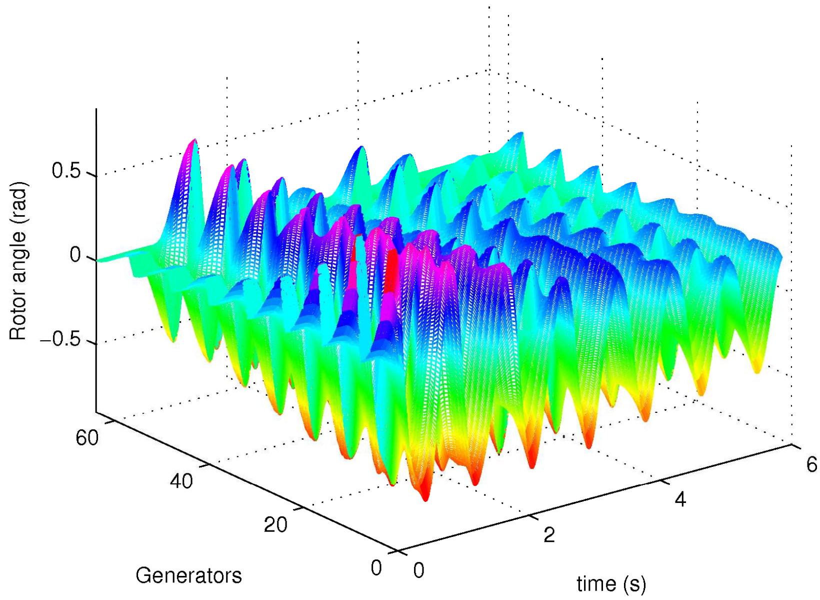

Figure 4. Propagation of electromechanical wave in rotor angle, referred to the rotor angle of machine $(8, 8)$, throughout the 2-D test system without FLPSS.

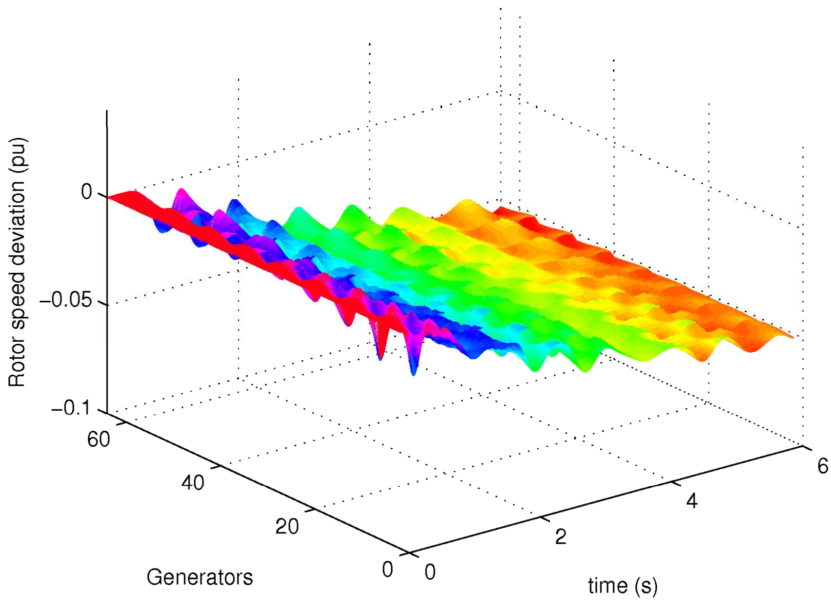

Figure 5. Propagation of electromechanical wave in rotor speed throughout the 2-D test power system without FLPSS.

speed deviation, when applying the conventional FLPSS, are shown in Figures 8 and 9 respectively.

When applying the proposed strategy, introduced in section 3., the new responses of machines' angles and speed deviations are shown in Figures 10 and 11 respectively. Putting Figures 8, 9, 10 and 11 in perspective, shows the improvement achieved when applying the proposed strategy of the FLPSS.

To allow a quantitative evaluation of the the proposed strategy, performance indexes $\sigma_\delta(t)$ and $\sigma_\omega(t)$ are proposed. They are defined as follows:

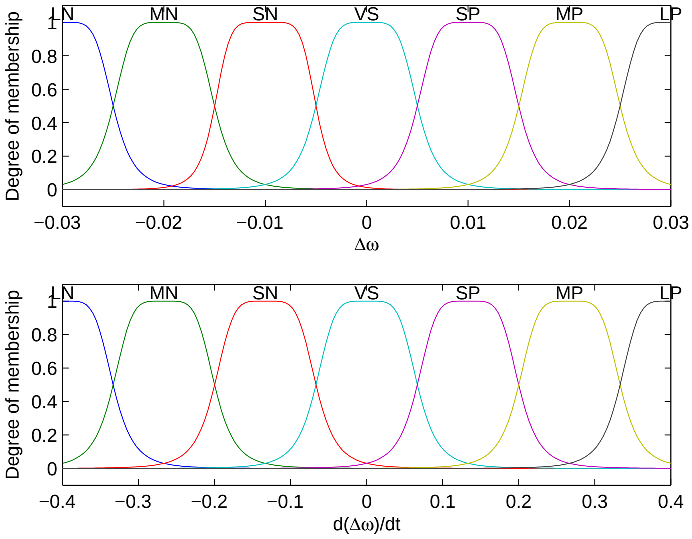

Figure 6. Membership function of the fuzzy inputs (the speed deviation ($\Delta\omega$) and the derivative of speed deviation ($\Delta\dot{\omega}$)).

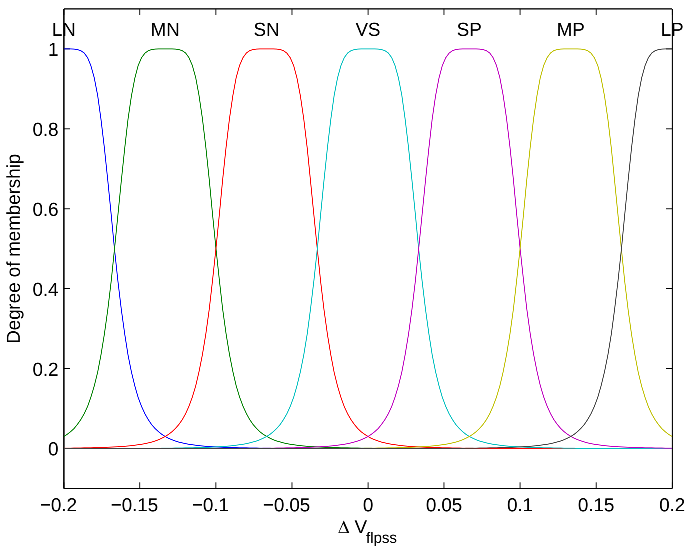

Figure 7. Membership function of the fuzzy output (ΔV_{flpss}).

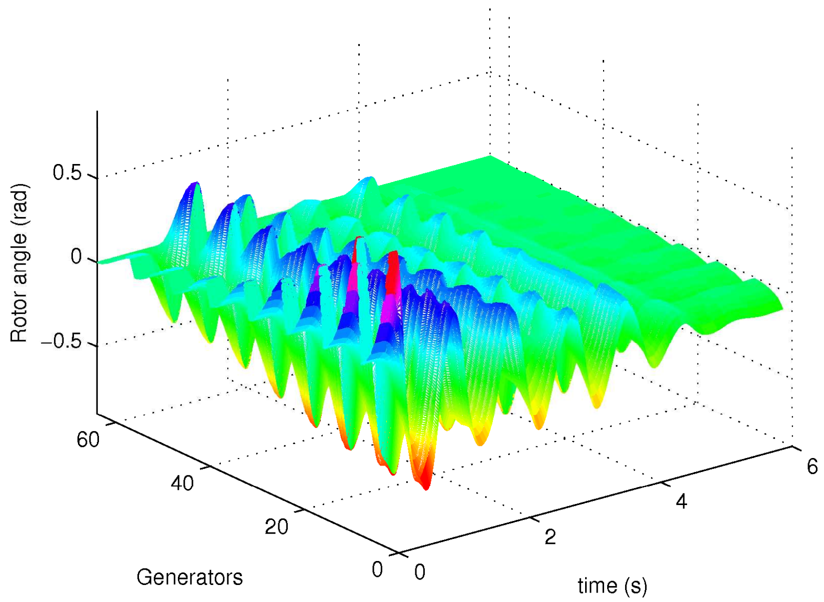

Figure 8. Rotor angle response for all machine (referred to machine(8,8)) with applying the conventional FLPSS.

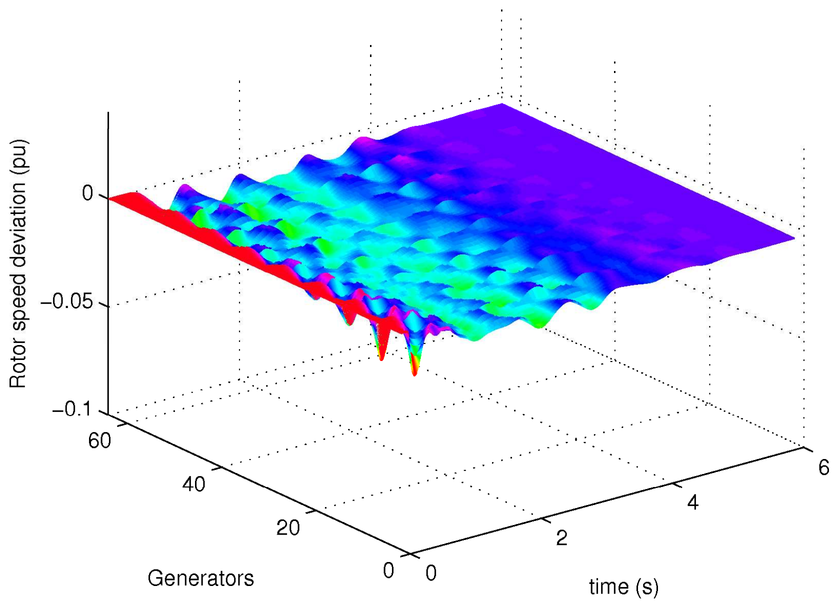

Figure 9. Rotor speed deviation of all machines with applying the conventional FLPSS.

$$\sigma_\delta(t) = \sum_{i=1}^{n}(\Delta\delta_i(t) - \Delta\delta_{COI}(t))^2 \tag{12}$$

$$\sigma_\omega(t) = \sum_{i=1}^{n}(\Delta\omega_i(t) - \Delta\omega_{COI}(t))^2 \tag{13}$$

These performance indexes consider two characteristics; First, the divergence from the center of inertia (COI) of rotor angle and speed deviation. Second, the speed of the controller to mitigate the disturbance propagation i.e., the time required for the performance index to reach zero.

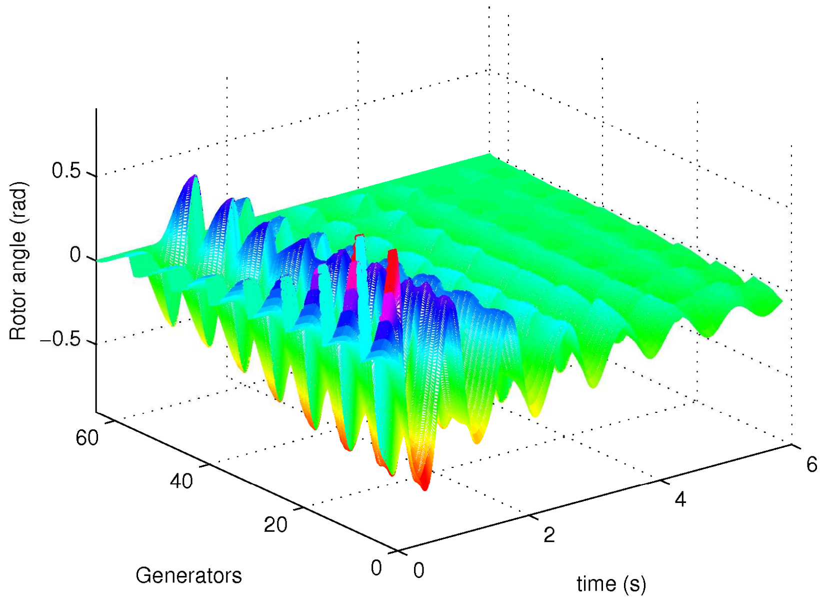

Figure 10. Rotor angle of all machines (referred to machine(8,8)) when applying the proposed strategy of FLPSS.

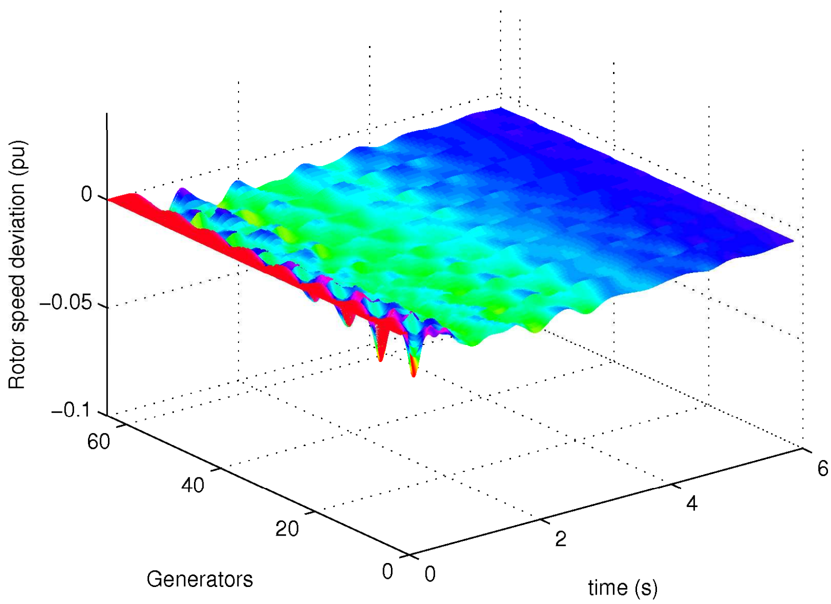

Figure 11. Rotor speed deviation of all machines when applying the proposed strategy of FLPSS.

To allow quantitative comparison between the conventional PSS, the conventional FLPSS and the proposed strategy of FLPSS, the performance indexes for speed deviation and for rotor angle are presented in Figures 12 and 13 respectively. Although the conventional FLPSS introduces some damping for the propagation of electromechanical wave, the proposed strategy of FLPSS add an additional damping for this propagation and for the associated oscillations.

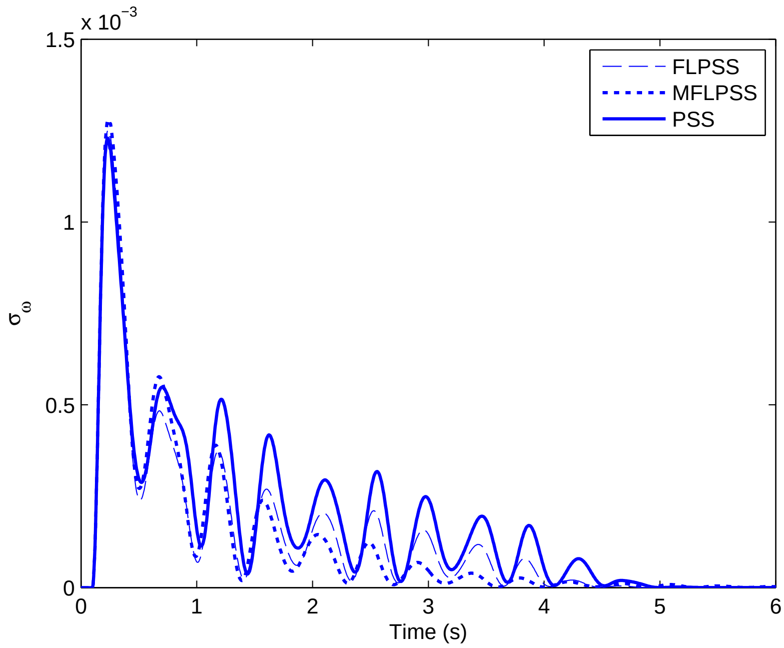

Figure 12. Comparison of the speed deviation performance indexes for PSS and FLPSS and proposed strategy of FLPSS (MFLPSS).

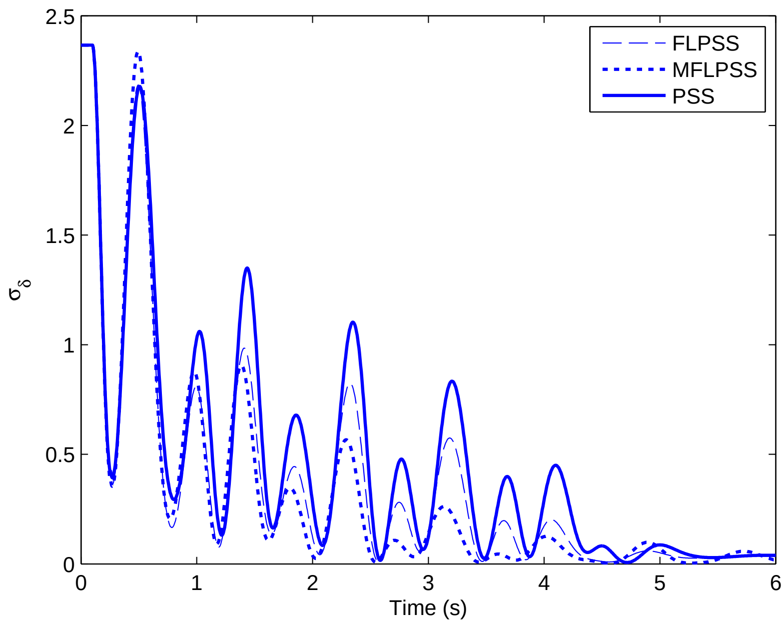

Figure 13. Comparison of the rotor angle performance indexes for PSS and FLPSS and proposed strategy of FLPSS (MFLPSS).

5. Conclusions

This paper presented a new strategy, based on the FLPSS, to improve the mitigation of the electromechanical wave propagation in power systems. The strategy is based on exploiting the speed deviation signals of the neighboring machines, via the FLPSS, to assist each other and to add additional damping torque. The importance of injecting the foremost machine FLPSS output signal to the excitation system of the latest machine is to counteract the propagating disturbance, where the time delay of propagation between neighboring machines is small. Also, the FLPSS output signals of the latest machines are injected into the excitation system of the foremost machines to oppose the reflected electromechanical wave upon reaching the system boundaries. The simulation results demonstrate that the application of the proposed strategy of FLPSS improves of the damping of the electromechanical wave propagation and the associated oscillations. However, the strategy still need some improvements, for example, variable gains of the auxiliary FLPSS signals can be used. Also, the communication system of the interconnected neighboring machines is needed to ensure the reliability of such a scheme.

Appendix

Referring to Figure 3, $Z_{tl} = j0.1\,pu$, $Z_l = (0.552 + j0.414)\,pu$. The generators are represented by detailed model, which has a field circuit on d-axis and one equivalent damper on q-axis. The machine parameters are identical, and they are as follows: $x\acute{}_d$ = $j0.067\,pu$, x_d = $j0.267\,pu$, $x\acute{}_q$ = $x\acute{}_d$, x_q = $j0.2\,pu$, T'_{d0} =$10\,s$, T'_{q0} =$0.5\,s$, and H =$5\,s$. The gains K_n and K_m are chosen the same for the identical machines of the uniform 2-D system and their optimized value is 0.015.

References

[1] A. Semlyen, “Analysis of disturbance propagation in power systems based on a homogeneous dynamic model,” *IEEE Transactions on Power Apparatus and Systems*, vol. 93, no. 2, pp. 676–684, March 1974.

[2] J. Thorp, C. Seyler, and A. Phadke, “Electromechanical wave propagation in large electric power systems,” *IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications*, vol. 45, no. 6, pp. 614–622, June 1998.

[3] M. Parashar, J. Thorp, and C. Seyler, “Continuum modeling of electromechanical dynamics in large-scale power systems,” *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 51, no. 9, pp. 1848–1858, September 2004.

[4] S. Tsai, L. Zhang, A. Phadke, L. Yilu, M. Ingram, S. Bell, I. Grant, D. Bradshaw, D. Lubkeman, and L. Tang, “Frequency sensitivity and electromechanical propagation simulation study in large power systems,” *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 54, no. 8, pp. 1819–1828, August 2007.

[5] R. Murphy, “Power system disturbance monitoring,” in *proc. of the Western Protective Relay Conference, Spokane, WA, USA*, 1994.

[6] A. Phadke, “Hidden failure in electric power systems,” *International Journal of Critical Infrastructures*, vol. 1, no. 1, pp. 64 – 75, 2004.

[7] D. Pavella, M. Ernst and D. Ruiz-Vega, *Transient Stability of Power System A unified Approach to Assessment and Control*, 1st ed. Kluwer Academic, October 2000.

[8] M. ALI, “Emergency control to prevent propagation of loss of synchronism,” in *in Proc. of the 15th international Middle East Power Systems Conference MEPCON’12, University of Alexandria, Alexandria, Egypt, 23-25 December*, 2012.

[9] P. Kundur, *Power System Stability and Control*, 1st ed. McGraw-Hill Professional, January 1994.

[10] M. Ali, J. Buisson, and W. Sabry, “Pss tuning to extinguish the spatial propagation of electromechanical disturbance in power system,” in *Proc. of the 41th North American Power Symposium NAPS2009, Mississippi, USA*, 4-6 October 2009.

[11] M. Ali, J. Buisson, and Y. Phulpin, “Improved control strategy to mitigate electromechanical wave propagation using pss,” in *Proc. of the 15th IEEE MELECON, Valletta Malta*, 25 - 28 April 2010.

[12] M. ALI, “Mitigation of electromechanical disturbance propagation in power systems,” Ph.D. dissertation, MATISSE, IETR-SUPELEC, University of Rennes1, November 2010.

[13] B. Lesieutre, E. Scholtz, G. Verghese, J. Thorp, and M. Parashar, “A zero-reflection controller for electromechanical disturbances in power networks,” in *proc. of the 14th Power Systems*

Computation Conference, Sevilla, Spain, 2002.

[14] K. Padiyar, *Power System Dynamics: Stability and Control*, 2nd ed. Anshan, August 2004.

[15] M. Hassan, O. Malik, and G. Hope, "A fuzzy logic based stabilizer for a synchronous machine," *IEEE Transactions on Energy Conversion*, vol. 6, no. 3, pp. 407–413, September 1991.

[16] K. El-Metwally and O. Malik, "Fuzzy logic power system stabiliser," *IEE Proceedings Generation, Transmission and Distribution*, vol. 142, no. 3, pp. 277–281, 1995.

[17] E. Larsen and D. Swann, "Applying power system stabilizers part i: general concepts," *IEEE Transactions on Power Apparatus and Systems*, vol. 100, no. 6, pp. 3017–3046, June 1981.

[18] M. El-Hawary, *Electric Power Applications of Fuzzy Systems*, 1st ed. Wiley-IEEE Press, June 1998.

[19] Y. Song and A. Johns, "Applications of fuzzy logic in power systems. i. general introduction to fuzzy logic," *Power Engineering Journal*, vol. 11, no. 5, pp. 219–222, 1997.

[20] J. Jantzen, "Design of fuzzy controllers," Technical University of Denmark, Department of Automation, Tech. Rep. 98-E-864, 1998.

[21] J. Jang, *Matlab Fuzzy Logic Toolbox: User's Guide*. MathWorks, 1997.

[22] S. Sivanandam, S. Sumathi, and S. Deepa, *Introduction to Fuzzy Logic using MATLAB*, 1st ed. Springer Verlag, December 2007.

[23] H. Toliyat, J. Sadeh, and R. Ghazi, "Design of augmented fuzzy logic power system stabilizers to enhance power systems stability," *IEEE Transactions on Energy Conversion*, vol. 11, no. 1, pp. 97–103, March 1996.

[24] K. Tang and R. Mulholland, "Comparing fuzzy logic with classical controller designs," *IEEE Transactions on Systems, Man, and Cybernetics*, no. 6, 1987.

[25] L. Huang, M. Parashar, A. Phadke, and J. Thorp, "Impact of electromechanical wave propagation on power system protection and control," *CIGRE Paris, France*, no. 34, pp. 201–206, August 2002.