Using auxiliary signals to attenuate 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— *The electromechanical wave propagation in power systems was emphasized and investigated through mathematical models and practical observations. To mitigate this propagation, the conventional power system stabilizer was introduced before. The strategy adopted in this paper is to exploit the phenomena of disturbance propagation and reflection to provide an extra damping torque via the PSS. To counteract the propagated disturbances, auxiliary signals of the speed deviation of the first disturbed machines are sent to the PSS of the consecutive directly connected machines. To enhance the overall damping, the reflected disturbances are considered as new propagated disturbances in the reverse direction and are counteracted as the propagated disturbances. In brief, the neighboring machines speed deviation signals are used as extra inputs to the PSS of each machine. The simplified model of the Western North American power grid and an academic power system model are simulated to illustrate the effectiveness of the proposed strategy to mitigate electromechanical wave propagation and the associated oscillations.*

Index Terms— **Electromechanical wave propagation, power system stabilizer PSS, interconnected machines**

I. INTRODUCTION

Faults and other random events cause a mismatch between the mechanical power input and the electrical power output in the generators of power systems. This power mismatch drives the generator rotors to move with respect to their synchronous reference frame. The disturbance propagates through the entire network as an electromechanical wave with a certain speed of propagation [1] [2]. This phenomenon is emphasized from simulation results [3], [4] and experimental observations [5]. Its speed of propagation depends on the generators and transmission system parameters [2].

The phenomenon of electromechanical wave propagation has different drawbacks on the power systems. It may stress power system equipments, e.g., generators and transformers, through the large oscillations which propagate to the entire network. It may cause malfunction of the protection system which leads to unexpected generator tripping, and consequently, the cascading failure occurs [6].

To avoid the drawbacks of the electromechanical wave propagation, two main trends of strategies could be developed [7], namely, preventive control strategies and emergency control strategies. The preventive control strategies advocate to operate the system with security margins that are high enough to decrease the likelihood of generator tripping. On the other hand, emergency control strategies could take appropriate actions in the aftermath of a disturbance to lessen the potential effect of the disturbance propagation [8].

The power system stabilizers (PSS) has been used many years ago to dampen electromechanical oscillations in power systems. They act through the excitation system in such a way that a component of electrical torque proportional to the speed change is generated as an addition to the damping torque, where the lack of sufficient damping torque results in oscillatory instability [9].

A controller strategy to extinguish the propagation of electromechanical disturbance was proposed in [10], in which the approach used was analogous to the impedance matching for transmission line to inhibit reflection of traveling electromagnetic waves. Tuned PSS with Genetic Algorithm and MATLAB built-in function (FMINCON) were introduced in [11] and [12] to dampen the propagation of electromechanical waves in power systems. In [13], [14], improvements were added to the conventional power system stabilizer through centralized and more decentralized strategies to mitigate the electromechanical disturbance propagation in power systems. These strategies are based on wide area measurements (WAM) to provide more efficient system damping.

The proposed approach, in this paper, consists thus of using neighboring signals to improve the operation of PSS in damping electromechanical wave propagation. The disturbance occurs at any place of the system tends to propagate to the entire system and is reflected when reaching the system boundaries. From the point of view of disturbance location, the foremost machines are the nearest to the first place of disturbance, and the latest machines are the most far. The speed deviation signals of the foremost machines can assist the damping of the propagated disturbance in the later machines through the PSS. To attenuate the disturbance reflection into the system, the speed deviation signals of the latest machines are also injected to the PSS of the foremost machines. Thus, each machine in the system is assisted by the speed deviation of all the interconnected machines to assist the damping provided by the PSS.

The paper is organized as follows. In Section II the modeling of the main components (generators and conventional PSS) and the effects of the electromechanical wave propagation on power systems are introduced. Section III demonstrates the proposed strategy to increase the damping of electromechanical wave propagation. Section IV presents an evaluation of the

proposed strategy. Finally, Section V presents the conclusion.

II. PROBLEM FORMULATION

This section introduces generator modeling and the associated conventional power system stabilizer. It refers also to the problems related to the electromechanical wave propagation.

A. Generator modeling

Different detailed models can represent synchronous machines depending on the degree of details [9] [15] [16]. In particular, the number of rotor windings and the corresponding state variables can vary from one to six [16]. In this paper, the adopted detailed model has a field circuit on the d-axis and one equivalent damper on the q-axis. The machine dynamic equations are presented as follows [16]:

$$\dot{E}'_q = \frac{1}{T'_{d0}}(-E'_q + (x_d - x'_d)i_d + E_{fd}) \tag{1}$$

$$\dot{E}'_d = \frac{1}{T'_{q0}}(-E'_d - (x_q - x'_q)i_q) \tag{2}$$

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

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

$$T_e = E'_d i_d + E'_q i_q + (x'_d - x'_q)i_d i_q \tag{5}$$

$$i_q = \Re e\{\frac{1}{r_a + jx'}[(E'_q + jE'_d) - (v_q + jv_d)]\} \tag{6}$$

$$i_d = \Im m\{\frac{1}{r_a + jx'}[(E'_q + jE'_d) - (v_q + jv_d)]\} \tag{7}$$

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.

The imbalance between electrical power output and mechanical power input, induces the generator rotor speed to deviate from the synchronous speed. To counteract the speed deviations, two principal controls have been developed for synchronous generators, namely the prime mover control and excitation control. The mathematical models of these controllers can be found in [9] [16].

PSS might be 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 [11] [12].

B. Conventional control of PSS

Conventional PSS have been used, for a long time, with local input signals, typically the rotor speed deviation, electrical power, or system frequency. This conventional control strategy is indeed efficient and succeeded, for large extent, to dampen different modes of oscillations [17], [18]. Usually, the PSS control strategy consists of three main stages: a gain, a signal washout and a phase compensation stage with maximum and minimum limits on the PSS output.

A schematic diagram of one type of conventional PSS acts upon a local signal (speed deviation) is shown in Figure 1.
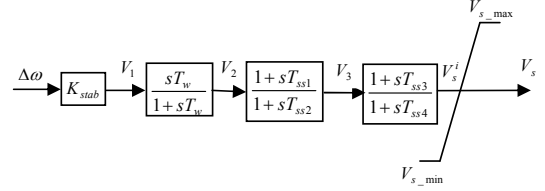

Fig. 1. Block diagram of a conventional PSS (speed deviation input).

This can be represented by the following equations.

$$V_1 = K_{stab}\ \Delta\omega \tag{8}$$

$$\dot{V}_2 = \frac{1}{T_w}(T_w\ \dot{V}_1 - V_2) \tag{9}$$

$$\dot{V}_3 = \frac{1}{T_{ss2}}(V_2 + T_{ss1}\ \dot{V}_2 - V_3) \tag{10}$$

$$\dot{V}^i_s = \frac{1}{T_{ss4}}(V_3 + T_{ss3}\ \dot{V}_3 - V^i_s) \tag{11}$$

$$V_s = \left\{ \begin{array}{ll} V_{s\_min} & if\ V^i_s \leq V_{s\_min} \\ V^i_s & if\ V_{s\_min} < V^i_s < V_{s\_max} \\ V_{s\_max} & if\ V^i_s \geq V_{s\_max} \end{array} \right\} \tag{12}$$

K_{stab} is constant gain, T_w is the washout time constant, T_{ss1}, T_{ss2}, T_{ss3}, and T_{ss4} are time constants for phase compensation, V_1, V_2, V_3 and V^i_s are intermediate variables, V_s is output of the PSS.

Although different techniques, such as linearization or optimization, are efficient in tuning PSS parameters, new strategies based on remote signals are proposed in the dense interconnected power system [19].

C. Problems related to the electromechanical wave propagation

The phenomenon of electromechanical wave propagation has significant effects on the power systems and their protection systems. As a local disturbance results in a deviation of the generator's rotor angle from its steady-state value, the propagation of this disturbance to all generators over the power network results in the extension of the rotor angle deviation, which affects the power transfers in the network and influences the reliable operation limits [2] [20].

The deviations in rotor angles influence the power flows, as the power flow between bus i and bus j in a pure inductive line is given by the following relation [20]:

$$P_{f_{ij}} = P_{max} sin\delta_{ij_0} \tag{13}$$

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:

$$P_{max} = \frac{V_{g_i} V_{g_j}}{X} \quad (14)$$

where V_{g_i} and V_{g_j} are the magnitude of the internal voltage of the two machines i and j and X is the reactance of the connecting line.

Assuming the angle δ_{ij_0} is small, the deviation in power transfer due to the small deviation in rotor angle difference, $\Delta\delta_{ij}$, is given by the following equations:

$$\Delta P_{f_{ij}} = P_{max}sin(\delta_{ij_0} + \Delta\delta_{ij}) - P_{max}sin\delta_{ij_0} \approx P_{max}\Delta\delta_{ij} \quad (15)$$

Therefore, a small change in the angle difference results in a change in power transfer, which could be significant and could impact the power system operation [14].

The effects of the electromechanical disturbance propagation on protection systems were presented in [20] [21] [22], 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 [21] [23]. The propagation of the electromechanical disturbance may trip over-current relays because of the transient increase of line currents over their pick-up setting. This unplanned tripping of over-current relays could disconnect one or some components of the power system, which may lead to other disturbances. The transient increase of line currents decreases the apparent impedance, assuming insignificant change in voltage magnitude, which may trip distance relays. These distance relays act usually to protect transmission lines, and therefore, their tripping cause an interruption of supplying the electrical power and may lead to a loss of loads and/or generators [14].

III. PROPOSED STRATEGY

The phenomenon of propagation and reflection of electromechanical waves in power systems are utilized in this proposed strategy. The strategy is based on injection neighboring speed deviation signals as extra inputs to the PSS of each machine to improve the damping of electromechanical wave propagation and the associated oscillations. More specifically, each machine' PSS has its local speed deviation signal beside the speed deviation signals of all the interconnected machines. The rationale behind using this strategy is that the speed deviation of the foremost machines, from the point of view of disturbance location, are injected into the PSS of the latest machines to add an extra damping to counteract the coming disturbance. Normally, there is a time delay 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 furthest. For neighboring machines, the time delay of propagation is very small. Moreover, the importance of injecting the speed deviation of the latest machines

into the PSS of the foremost machines is to counteract the electromechanical wave reflection upon reaching the system boundaries [21].

The proposed strategy introduced in this paper differs from those proposed in [13], [14], in some points;

- There is no need for WAM signals and the associated difficulties.
- The speed deviation signals of the nearby machines are not delayed by the time delay, as in [14], because of the small time delay of the disturbance between nearby machines.
- All the speed deviation signals of interconnected machines are used interchangeably to provide extra damping for the wave propagation and reflection wherever the source of the disturbance.

Equation 8 is modified to include the proposed inputs to the conventional PSS of machine n as follows:

$$V_1 = K_{stab} \left(\Delta\omega_n + \sum_m K_m\Delta\omega_m\right) \quad (16)$$

$\Delta\omega_n$ is the local speed deviation of the machine itself and $\Delta\omega_m$ represents the speed deviation signals of all the machines interconnected with machine n and K_m represents the associated gain. According to the modification of Equation 8, the consecutive equations are adapted to apply the proposed modification. A schematic diagram of the proposed strategy is shown in Figure 2. The effective damping is achieved when
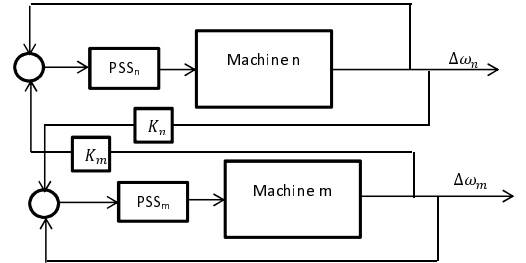

Fig. 2. A schematic diagram of the modifications of the conventional PSS.

the supplementary damping torque and the conventional PSS damping torque are in phase. For the adjacent machines, the time delay between the arrivals of the disturbance is small, and hence it can be compensated by the communication time delay between the adjacent machines.

IV. EVALUATION OF THE PROPOSED STRATEGY

This section presents an evaluation of the proposed strategy through the simulation of two models with the application of the proposed modification of the PSS. The simulated models are the uniform two-dimensional (2-D) model and the modified model of the Western North American power system (WNAPS).

A. uniform 2-D system

The uniform 2-D system is a regular grid as shown in Figure 3. It consists of a 2-D grid of 8×8 nodes, where one generator and a shunt load are connected to each node. The transmission

lines connecting two adjacent nodes are identical and are represented by a reactance Z_{tl}, while the loads are modeled with constant impedance Z_l. The sequence of fault conditions
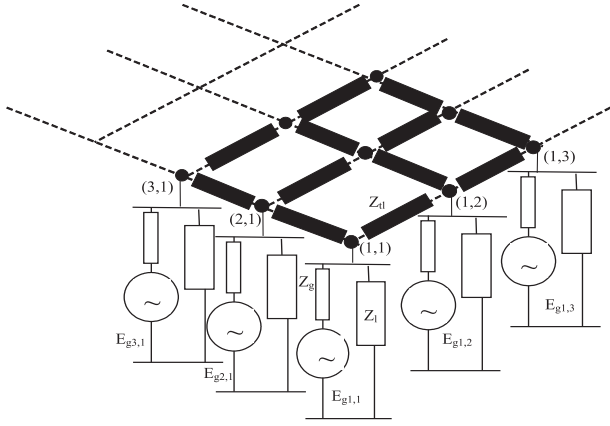

Fig. 3.   Uniform power system model arranged in a grid of two dimensions.

is 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. These fault conditions initiate a disturbance, which propagates to the entire network in two dimensions x and y. The propagated disturbance in rotor speed deviation of the 64 generators of the 2-D model is shown in Figure 4, where all the machines are equipped with the prime mover and the excitation system without PSS. This
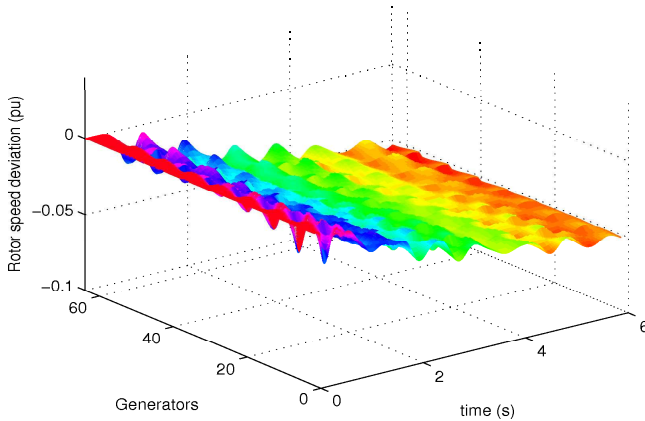

Fig. 4.   Propagation of electromechanical wave in rotor speed throughout the uniform 2-D test model.

Figure shows that the disturbance occurs at the first generator causes local electromechanical oscillations at this generator. This disturbance propagates all over the network causing not only oscillations at each generator but also it is reflected back as a new disturbance. So the problem is twofold; firstly, the electromechanical oscillation occurs at each generator due to the propagation of the disturbance. Secondly, the refection of the disturbance, at network edges, back into the network causing a new disturbance in the reverse direction.

B. Application of PSS and 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 speed deviations with the conventional PSS, tuned with system linearization, are shown in Figure 5. The new
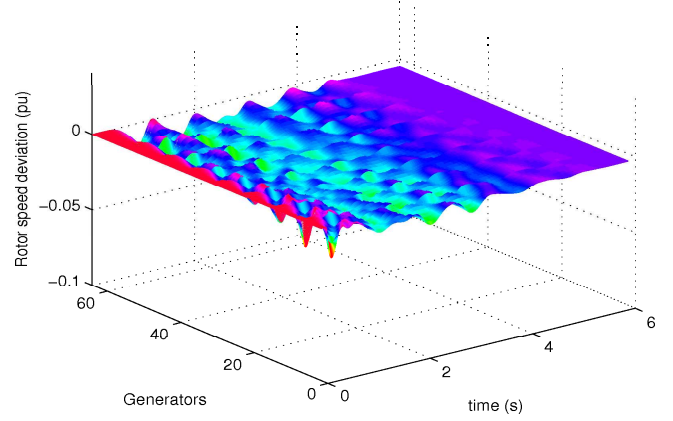

Fig. 5.   Rotor speed deviation of all machines with applying the conventional PSS.

responses of machines' speed deviations, with applying the proposed strategy, are shown in Figure 6.
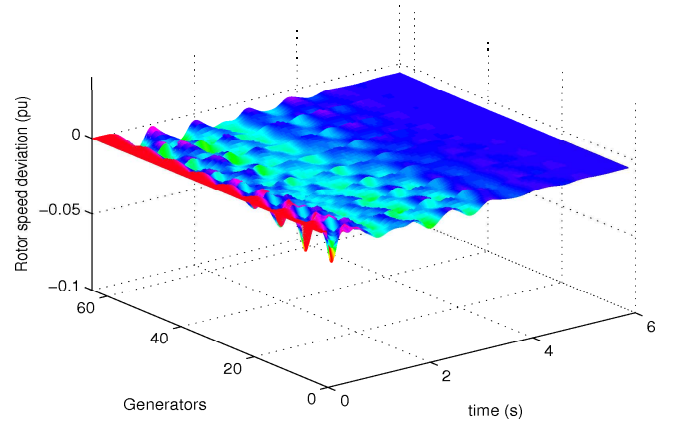

Fig. 6.   Rotor speed deviation of all machines with injecting the auxiliary Signals to the conventional PSS.

Figure 7 shows also the improvement of the responses of rotor angles of selected machines with injecting the auxiliary signals to the conventional PSS. All rotor angles are referred to machine(8,8). It is shown that the conventional PSS introduces some damping for the propagation of electromechanical wave in rotor angle and speed, whereas the injecting of the auxiliary signals to the conventional PSS improves the rotor angle and speed deviation responses. The parameters of the conventional PSS and the proposed modifications are given in the Appendix.

C. Simplified model of the Western North American power grid

The simplified model of the Western North American power system (WNAPS) was studied with different types of simpli-
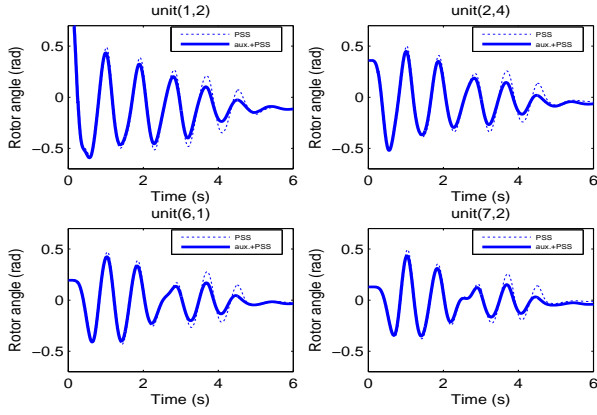
Fig. 7. Rotor angle of selected machines before and after injecting the auxiliary signals to the conventional PSS.

Fig. 9. Propagation of electromechanical disturbance in rotor speed deviation through the modified WNAPS for a loss of generation at bus 1.

fications [24]. The modified model of the WNAPS is shown in Figure 8. The data of generators and transmission lines can be found in [14] [24]. To demonstrate the propagation of the
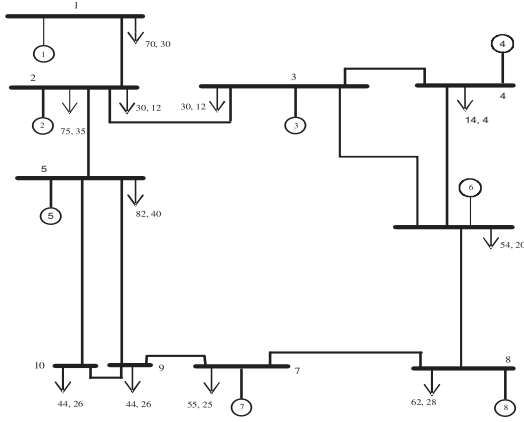

Fig. 8. The modified model of the simplified Western North American test system

electromechanical disturbance over the modified WNAPS, a loss of generation fault is applied at bus 1 at $t = 0.1\ s$. This disturbance propagates to the entire network as presented in Figure 9, where the rotor speed deviations of all machines are presented. It can be shown that the propagation of disturbance in the modified WNAPS is less distinct than that of the 2-D test power systems because of its non-uniformity. However, there are different delays in the beginning of the disturbance at each machine, which emphasize the propagation of the disturbance to the entire power network.

D. Application of PSS and the proposed strategy to the modified WNAPS

The proposed strategy is applied, with the operation of the conventional PSS tuned with system linearization, to the modified model of the WNAPS. To explain this strategy for the simulated system, as machine 1 is lost, the speed deviation signal of machine 2 is sent to the PSS of all the electrically adjacent machines, i.e., machine 3 and machine 5 and also the
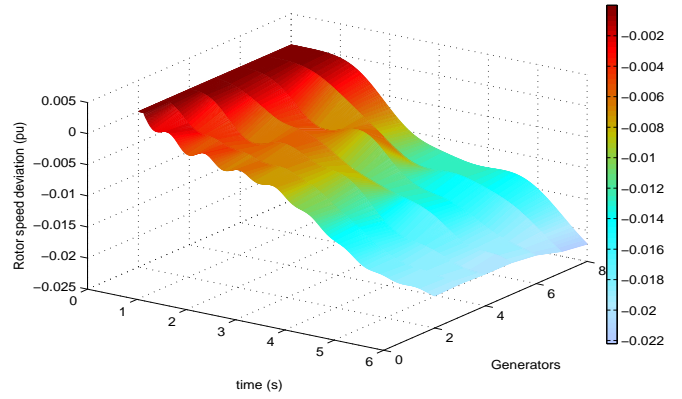
speed deviation signal of machines 3 and 5 are sent to the PSS of machine 2 and so on.

To show the improvement achieved by the application of the proposed strategy, the responses of rotor speed deviations with applying the proposed strategy are shown in Figure 10. A comparison with the application of the conventional PSS
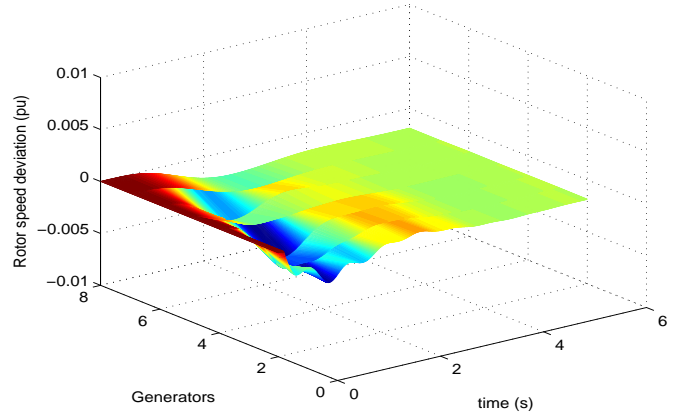

Fig. 10. Rotor speed deviation of all machines of the modified WNAPS with applying the proposed strategy to modify PSS.

only, for selected machines, is shown in Figure 11. Also, a comparison is made for the rotor angles of selected machines, as shown in Figure 12, to emphasize the strength of the proposed strategy.

V. CONCLUSIONS

This paper presented a new strategy to attenuate the electromechanical wave propagation in power systems equipped with PSS. The strategy is based on employing the speed deviation signals of the neighboring machines to add extra damping to the operation of the PSS. The importance of injecting the foremost machines' speed deviation signals to the latest machine PSS is to counteract the propagating disturbance. Also, the speed deviation signals of the latest machines are injected into the PSS of the foremost machines to oppose the reflected wave upon reaching the system boundaries. The simulation results show that the application of the proposed
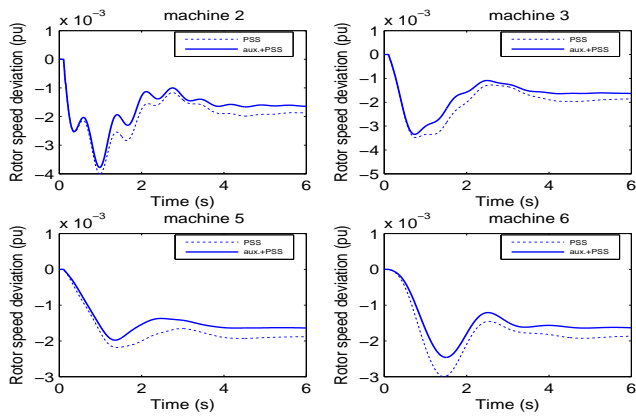
Fig. 11. Rotor speed deviation of machines $2, 3, 5$ and 6 of the modified WNAPS before and after applying the proposed strategy to modify PSS.
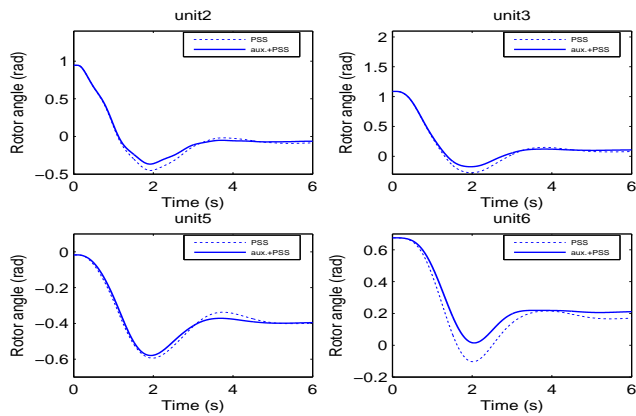

Fig. 12. Rotor angles of machines $2, 3, 5$ and 6 of the modified WNAPS before and after applying the proposed strategy to modify PSS.

strategy leads to the improvement of the attenuation of the electromechanical wave propagation and to improve system dynamics. However, some improvements of the strategy still needed, for example the method of determination of the gains of the injected signals. Also, the reliability of such a scheme must be considered, where, a communication system of the interconnected neighboring machines is needed.

APPENDIX

Referring to Figure 3, $Z_{tl} = j0.1\,pu$, $Z_l = (0.552 + j0.414)\,pu$. The machine parameters are identical, and they are as follows: $x'_d = j0.067\,pu$, $x_d = j0.267\,pu$, $x'_q = x'_d$, $x_q = j0.2\,pu$, $T'_{d0} = 10\,s$, $T'_{q0} = 0.5\,s$, and $H = 5\,s$. The parameters of the PSS and the proposed strategy are as follows: $K_{stab} = 20$, $T_w = 10$, $T_{ss1} = 0.04$, $T_{ss2} = 0.02$, $T_{ss3} = 0.04$, $T_{ss4} = 0.02$, and $K_m = -0.15$. The machines and the PSS parameters of the modified WNAPS can be found in [14], and the gains associated with the neighboring speed deviations are chosen to be $K_m = -0.15$.

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. G. Phadke, "Hidden failures 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] 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.

[11] 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.

[12] M. N. Ali, "Tuning pss to mitigate the propagation of electromechanical oscillation in power systems," *Advances in Electrical Engineering Systems (AEES)*, vol. 1, no. 4, pp. 201–206, 2013.

[13] 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.

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

[15] W. Stevenson, *Elements of Power System Analysis*, 4th ed. McGraw-Hill, September 1982.

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

[17] G. Rogers, "The application of power system stabilizers to a multigenerator," *IEEE Transactions on Power Systems*, vol. 15, no. 1, pp. 350–355, February 2000.

[18] K. Lee, B. Hydro, and B. Vancouver, "Analysis of power system stabilizers application for controlling poorly damped oscillations in the alcan/bc hybrid power systems," *IEEE Transactions on Power Systems*, vol. 8, no. 1, pp. 255–263, February 1993.

[19] M. Aboul-Ela, A. Sallam, J. McCalley, and A. Fouad, "Damping controller design for power system oscillations using global signals," *IEEE Transactions on Power Systems*, vol. 11, no. 2, pp. 767–773, May 1996.

[20] L. Huang, M. Parashar, A. Phadke, and J. Thorp, "Effects of electromechanical wave propagation on protection systems," in *Proc. of the International Conference on Power Systems and Communication Systems Infrastructures for the Future, Beijing, China*, 2002.

[21] ——, "Impact of electromechanical wave propagation on power system protection and control," *CIGRE Paris, France*, no. 34, pp. 201–206, August 2002.

[22] L. Huang, "Electromechanical wave propagation in large electric power systems," Ph.D. dissertation, Virginia Polytechnic Institute and State University (Virginia Tech), 2003.

[23] S. Horowitz and A. Phadke, *Power System Relaying*, 3rd ed. Wiley, June 2008.

[24] D. Trudnowski, J. Smith, T. Short, and D. Pierre, "An application of prony methods in pss design for multimachinesystems," *IEEE Transactions on Power Systems*, vol. 6, no. 1, pp. 118–126, February 1991.