Improved Control Strategy to Mitigate Electromechanical Wave Propagation Using PSS

Mahmoud Ali #1, Jean Buisson #2, Yannick Phulpin *3

SUPELEC/IETR
Rennes, France
[1] mahmoud.ali@supelec.fr

[2] jean.buisson@supelec.fr

* *SUPELEC*
Gif-sur-Yvette, France

[3] yannick.phulpin@supelec.fr

***Abstract*— This paper addresses the problem of electromechanical wave propagation in power systems. To mitigate this type of disturbance, this paper proposes a remote control strategy that could be applied to power system stabilizers. This strategy is based on wide-area measurements, and exploits the disturbance propagation speed to introduce an extra damping torque simultaneously with the disturbance arrival. Simulation results show that the application of such strategy improves the power system dynamics.**

***Index Terms*— Electromechanical wave propagation, power system stabilizer, wide-area measurements.**

I. Introduction

Power systems oscillations usually result from electromechanical disturbances induced by local imbalance between the mechanical power received by generators and their respective power injection into the grid. They can be broadly classified into three categories: positively damped, sustained, and negatively damped oscillations. Sustained and negatively damped oscillations can be harmful, as they can lead to system collapse if their amplitude is too large [1]. As introduced in [2], electromechanical disturbances can propagate all over interconnected power networks. This phenomenon is emphasized from simulation results [3], [4] and experimental observations [5]. Its attributes (e.g., speed of propagation, amplitude, damping) depend on the generators and transmission system parameters, and on the initial disturbance [6].

Damping electromechanical wave propagation is an important issue, as this kind of disturbance may stress power system equipments, e.g. generators and transformers, and cause generator tripping, which might eventually lead to cascading failure [7]. To avoid unnecessary emergency control actions, electromechanical wave propagation must be mitigated. Two main trends of strategies have been developed [8]. On one hand, 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.

Power system stabilizers (PSS) have been used for many years to dampen electromechanical oscillations. Basically, 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 extra damping torque, where the lack of sufficient damping torque results in oscillatory instability [9] [10]. A number of control strategies to dampen oscillations in power systems have been investigated recently. More specifically, two main trends have arisen. A first approach is based on local measurements and generally depends on fine tuning of PSS and/or allocation of minimal number of coordinated stabilizers [11]. The second approach is based on wide-area measurements and uses a large amount of information from remote locations in the system to provide more efficient system damping [12]. A major drawback of the second approach is the need for additional communication facilities and the associated time delay [13], [14]. However, the recent development of simultaneous measurement of rotor angle and frequency through synchronized phasor measurement units [15] and frequency disturbance recorders [16] tends to ease remote control in power systems.

The proposed approach consists thus of using remote control to make the best use of PSS in damping electromechanical wave propagation. It is based on wide-area measurements (e.g., generator speeds) and exploits the disturbance propagation speed to enhance the operation of PSS. Also, the time delay related with wide-area signal measurement, processing, and transmission is considered.

The paper is organized as follows. In Section II, we introduce a formalization of the problem as an improvement of conventional power system stabilizer control strategies. Section III presents the proposed modifications for the conventional PSS to ensure better damping of electromechanical wave propagation. Section IV presents a benchmark system, and illustrates the problem of electromechanical wave propagation. In this context, the system responses with the conventional PSS and the proposed improvement are compared. Finally, Section V concludes and presents new research directions.

II. Formalization of the Problem

This section aims to formalize the problem of mitigating electromechanical wave propagation. After describing already

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existing control schemes in power systems, it details the expectations for a new improvement of PSS.

A. Generator Control

The mismatch between electrical power output and mechanical power input, induces changes in generator rotor speed, which may eventually deviate from the synchronous speed. The amplitude of the associated disturbance varies according to the generator's attribute (e.g., inertia, initial conditions), and fault type and duration. To limit generator's speed deviations, two main control layers have been developed for synchronous generators, namely the prime mover control and excitation control.

Whereas, the prime mover control consists of adjusting the mechanical power depending on the generator speed, the synchronous generators' excitation system consists of an exciter that supplies the generator with a controlled DC field current. The excitation setting is externally defined, and an automatic voltage regulator (AVR) regulates the generators' terminal voltage by controlling the generator field current supplied by the exciter. PSS might be added to the excitation system to dampen power system oscillations. Typically, PSS is a differentiating element with phase shifting corrective elements and its input signals is proportional to the rotor speed, frequency and/or electrical power output [17]. Figure 1 presents the general functional of generator excitation control system [18]. Despite the presence of the above described

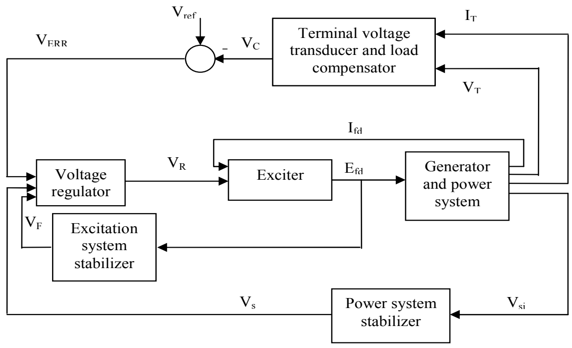

Fig. 1. Block diagram of general functional of excitation control system.

usual types of control, electromechanical wave propagation and the associated oscillations of generator rotor can not be completely damped, and the fast acting exciter with high gain AVR can even contribute to the oscillatory instability in power systems [19]. A satisfactory solution for this problem is the appropriately designing of power system stabilizers' parameters.

B. Conventional Control of PSS

For a long time, PSS have been used with locally measured 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 [20], [21]. 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 combination of some local signals (speed deviation and accelerating power) is shown in Figure 2. This can be

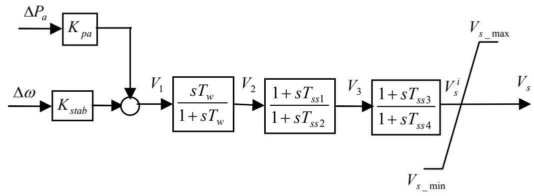

Fig. 2. Block diagram of a conventional PSS.

represented by the following equations:

$$V_1 = (K_{pa}\ \Delta P_a + K_{stab}\ \Delta\omega) \tag{1}$$

$$\dot{V}_2 = \frac{1}{T_w}(T_w\ \dot{V}_1 - V_2) \tag{2}$$

$$\dot{V}_3 = \frac{1}{T_{ss2}}(V_2 + T_{ss1}\ \dot{V}_2 - V_3) \tag{3}$$

$$\dot{V}_s^i = \frac{1}{T_{ss4}}(V_3 + T_{ss3}\ \dot{V}_3 - V_s^i) \tag{4}$$

$$V_s = \left\{ \begin{array}{ll} V_{s\_min} & if\ V_s^i \leq V_{s\_min} \\ V_s^i & if\ V_{s\_min} < V_s^i < V_{s\_max} \\ V_{s\_max} & if\ V_s^i \geq V_{s\_max} \end{array} \right\} \tag{5}$$

where P_a is the accelerating power, K_{pa} and K_{stab} are 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_s^i are intermediate variables. To achieve an efficient operation of PSS, its parameters need to be finely tunned.

As the interconnected power networks become more and more sophisticated, each generator response is affected by the responses of the neighboring generators. Also, with the advance in wide-area measurements, research tends to propose new strategies based on remote signals [22].

C. Electromechanical Wave Propagation Problem

Tests based on synchronized PMU measurements have shown glimpses of electromechanical wave propagation [23], [3]. This wave has a certain speed of propagation, which is dependent on bus voltages, system frequency, machine inertias and transmission line impedances [6].

In [6], the speed of propagation of the electromechanical wave in a uniform continuum model of a ring power system was derived as:

$$v = \sqrt{\frac{w_N V^2 \sin\theta}{2h\,|z|}} \tag{6}$$

where v is the wave propagation speed, w_N is the nominal system frequency, V is the magnitude of the source voltage, θ is the phase angle of the transmission line impedance, h is the inertia constant per unit length and z is the per unit transmission line impedance per unit length.

The conventional power system stabilizer operation can be improved if the delay of the electromechanical wave propagation is exploited to add an additional damping torque, when the disturbance occurs.

III. Proposed Strategy

In the proposed control strategy, the phenomenon of electromechanical wave propagation in power system are exploited to design a new controller, based on wide-area measurements, to assist the operation of PSS at each machine to improve the damping of electromechanical wave propagation and the associated oscillations.

This control strategy is based on two signals, respectively local and remote. The remote signal based control is based on the phenomenon of disturbance propagation, which involves a propagation speed, i.e. a certain time delay. Indeed, if a disturbance occurs at certain place of the system, the foremost affected units are the nearest to the fault location and the last affected units are the most far.

This phenomenon can be employed in designing a controller with an input of the speed of the unit closest to the fault location. This speed signal is compared to the system average speed and the error signal is amplified and is delayed with a certain time. This time delay is needed to provide the PSS with the supplementary signal, of the proposed controller, at the expected time of arrival of the propagated disturbance. So, the controller action makes an anticipation to the arrival of the disturbance and counteracts its effect. In brief, the output signal of the proposed controller is sent to all PSS, located at each unit, with a time delay, which corresponds to the estimated time delay of disturbance propagation.

The system average speed, ω_{COI}, which is an input signal in the proposed controller, is the center of inertia (COI) of all machines' speeds and can be calculated according to the following equation:

$$\omega_{COI} = \sum_{i \in n} M_i * \omega_i / \sum M_i \tag{7}$$

where n is the total number of generators in operation, M is the inertia constant. To employ ω_{COI} in the proposed controller, rotor speeds of all machines need to be measured and processed, which impose a certain time delay of wide-area measurement and processing.

The controller with local signal is used to add an additional damping torque to that of the remote signal controller and to ensure overall controller reliability in case of occurrence of malfunction or communication problem to the remote signal controller. The local signal controller comprises a differentiation of the local rotor speed deviation, a gain and a filter with small time constant.

The schematic diagram of the proposed modification to the conventional PSS is shown in Figure 3. The equations represent the proposed controller to be added to the conventional PSS are as follows:

$$\dot{V_l} = \frac{1}{T_l}(K_l \ \dot{\Delta\omega} - V_l) \tag{8}$$

$$V_w^i = K_w \ (\Delta\omega_{COI} - \Delta\omega_c) \tag{9}$$

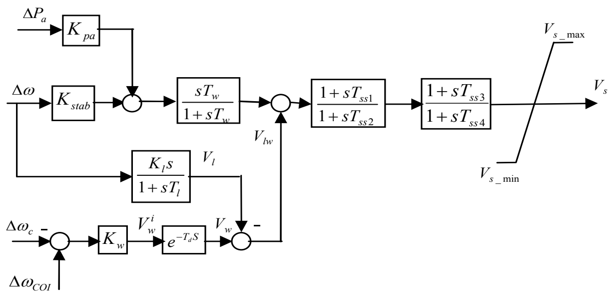

Fig. 3. Block diagram of the proposed modification of PSS.

$$V_w(t) = V_w^i(t - T_d) \tag{10}$$

$$V_{lw} = V_w - V_l \tag{11}$$

where K_l is the gain of the controller with local signal input, T_l is the time constant of the filter of the local signal controller, K_w is the gain of the controller with remote signal, T_d is the time delay utilized with the controller with remote signal, $\Delta\omega_c$ is the speed deviation of the nearest unit to the fault location.

The proposed controller utilizes the error signal (the difference between the system average speed and the speed deviation of the nearest unit to the fault location), to produce supplementary damping torque, which is not in phase with the damping torque produced by the conventional PSS at each unit. To achieve a good damping, the supplementary damping torque and the conventional PSS damping torque need to be in phase. This can be done by introducing a time delay for the supplementary damping torque according to the time of disturbance propagation from the first disturbed unit (the nearest unit to the fault location) to all the other units. So when the propagated disturbance arrives at a certain machine, the delayed supplementary damping torque increases the damping torque of conventional PSS.

The time delay needed in the proposed controller depends on some factors such as machine inertia, bus voltage and transmission line impedance [6]. So, the propagation delay does not depend on the disturbance itself and this delay can be estimated from off line simulation.

The time delay of propagation used in the controller design may be changed to take into consideration a certain limitation, which is imposed by the time delay for measuring and processing the remote signals. So, the wide-area measurement time delay will limit the designed time delay of the propagation especially for the nearby units to the fault location. So, the new time delay used in the proposed controller will be constrained by the wide-area measurement time, i.e., the designed time delay must be greater than or equal the wide-area measurement time delay.

IV. Evaluation of the Proposed Strategy

A. System Model

The power system under study is shown in Figure 4. It consists of $8 * 8$ node grid, where one generator and a shunt load are connected to each node. For example, one node is represented in Figure 5. The generators are represented by detailed model, which has a field circuit on d-axis and one equivalent damper on q-axis, with modeling of the excitation system and governor action.

All transmission lines connecting two adjacent nodes are identical. They are represented by a reactance $Z_{tl} = j0.1\,pu$, while the loads are modeled with constant impedance $Z_l = (0.552 + j0.414)\,pu$. The machine parameters, with the exception of machine (1,1), 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=2.5. The test power system is subjected to

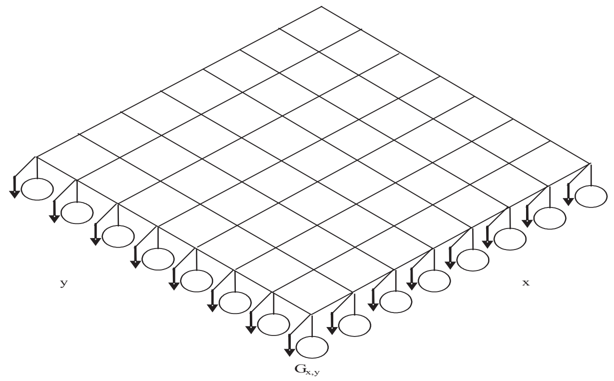

Fig. 4. Power system network simulated arranged in a grid of two dimensions.

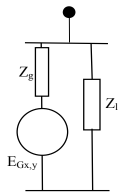

Fig. 5. One node representation.

a sequence of events to generate the simulation results as the following:

Before $t = 0.1\ s$, the system is in steady state.

At $t = 0.1\ s$, the generator at bus (1,1), which has the largest contribution in the power production, is disconnected.

These fault conditions cause a disturbance in rotor angle and speed, which propagates through the entire network.

B. Simulation of Proposed Control

The control strategy, presented in section III, is applied to the power system under study. The signal w_c is considered as the speed of unit (1,2) or the speed of unit (2,1), where they have the same maximum speed deviation and they are at the same distance from the faulted bus.

The time delay of propagation of disturbance in generator speed between each two adjacent units depends on some parameters such as generator inertia, line impedance, etc. To estimate the time delay of the disturbance propagation, one of two procedure may be adopted. The first procedure is to set an arbitrary small value of speed deviation and calculate the first time at which each generator speed deviation attains this value and the time delay between each units can be calculated. The second procedure, which is adopted in this work, is to measure the time at which each machine speed deviation attains its first peak and the time delay of propagation between any two generators is the difference between the time of their first peaks. As mentioned in Section III, the propagation time delay depends mainly on the machine and network parameters, i.e., the propagation delay can be estimated from the off line simulation. The time of the first peak of each machine speed, obtained from the simulation results of the test power system, is shown in Table I. From this table, the time delay

TABLE I

TIME (IN ms) AT WHICH EACH GENERATOR SPEED DEVIATION REACHES THEIR FIRST PEAKS AFTER FAULT OCCURRENCE.

units	1	2	3	4	5	6	7	8
1		85	145	200	255	315	380	415
2	85	130	170	215	270	330	390	425
3	145	170	205	245	290	350	410	440
4	200	215	245	280	325	380	440	465
5	255	270	290	325	370	425	480	500
6	315	330	350	380	425	490	525	535
7	380	390	410	440	480	525	550	560
8	415	425	440	465	500	535	560	570

of propagation between any two units can be calculated. For example, the time delay between unit (1,2) and unit (1,3) can be calculated as $145 - 85 = 60\ ms$. So the time delay of propagation of all units with respect to unit (1,2) can be calculated.

The proposed controller exploits this propagation delay to send a delayed signal to assist all the conventional PSS controllers installed at each unit at the proper time the propagated disturbance arrives. In designing this proposed controller, system average speed ω_{COI} is also exploited as an input signal, which imposes a time delay of wide-area measurement as mentioned in Section III.

The time delay due to wide-area measurements comprises certain time delays such as transducer delay, processing delay, multiplexing and transitions, and communication link involved. For estimating the time delay due to wide-area measurements, Reference [13] estimates the combined delay caused by processing, multiplexing, and transducers, for 10-12 phasor measurements, to be around 75 ms. The communication time is dependent on the medium used, e.g., for Fiber-optics cables the associated delay is about $100 - 150\ ms$ [13].

The overall wide-area measurements time delay considered, in our case, is estimated to be 200 ms. The wide-area time delay is a constraint for the time delay used in the proposed controller. So, the time delay used in the proposed controller must be greater than or equal the wide-area measurement time delay.

To adjust the parameters of the PSS and the new controller, the genetic algorithm optimization toolbox of MATLAB is used to minimize an objective function, F_{obj}, which is given as follows [24]:

$$F_{obj} = \sum_{i=2}^{n} \int_0^{t_f} (\Delta\omega_i)^2\ dt \tag{12}$$

where t_f is the period of simulation. The optimized parameters are as follows: $K_{stab} = 10$, $K_{pa} = 0.14$, $T_w = 10$, $T_{ss1} =$

0.99, $T_{ss2} = 0.2693$, $T_{ss3} = 0.0481$, $T_{ss4} = 0.2702$, $K_l = 2$, $T_l = 0.1\ s$, $K_w = 10$.

To evaluate the proposed strategy, we introduce some simulation results in order to be compared with those of the conventional PSS. The rotor angle and rotor speed deviation are examined to evaluate the effectiveness of this strategy.

First, we introduce the responses of all rotor angles, referred to the angle of unit (8,8), and all rotor speed deviations with the conventional PSS as shown in Figures 6 and 7 respectively.

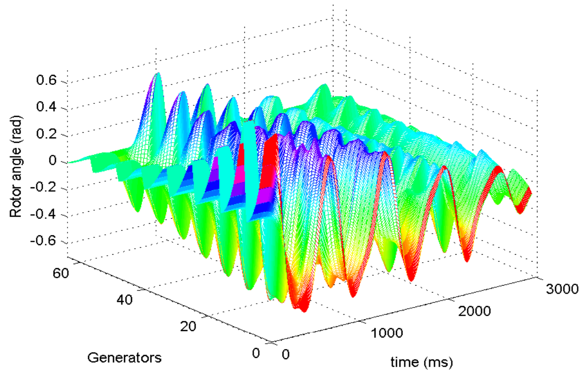

Fig. 6. Rotor angle response for all machine (referred to machine(8,8)) with applying the conventional PSS.

With applying the new controller, introduced in section III, the

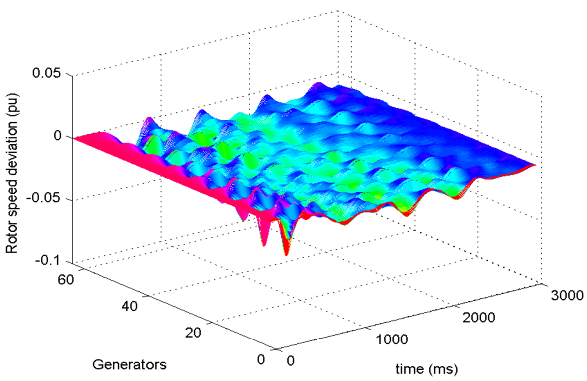

Fig. 7. Rotor speed deviation of all machines with applying conventional PSS.

new responses of machines' angles and speed deviations are shown in Figures 8 and 9 respectively. Although the conventional PSS introduces some damping for the propagation of electromechanical wave, the proposed modifications for the conventional PSS add an additional damping for this propagation. To clarify these improvements, selected machines' angles and speed deviations are presented, respectively, in Figures 10 and 11 to give proximate views for the comparison between the responses before and after applying the modifications of conventional PSS. The improvement in the electromechanical wave propagation damping with the new controller is due to providing an auxiliary damping torque in a proper time to assist the damping torque provided by the conventional PSS.

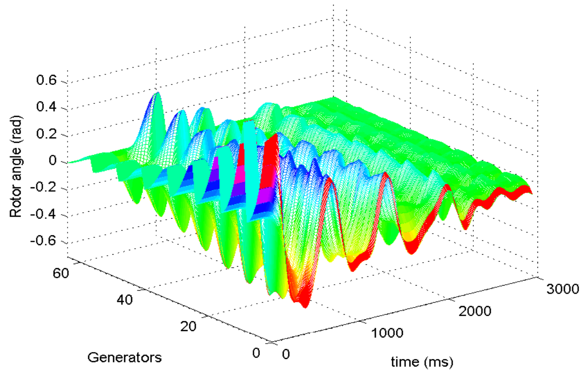

Fig. 8. Rotor angle of all machines (referred to machine(8,8)) with applying the proposed modifications of conventional PSS.

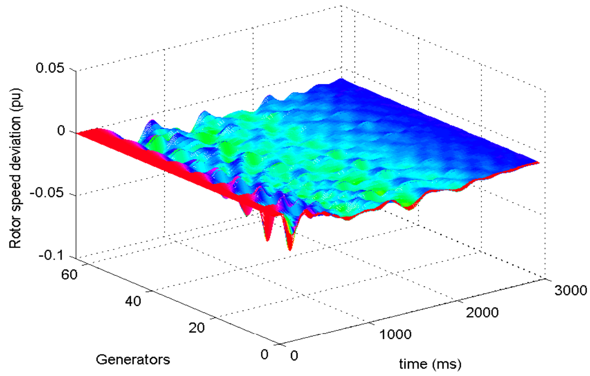

Fig. 9. Rotor speed deviation of all machines with applying the proposed modifications of conventional PSS.

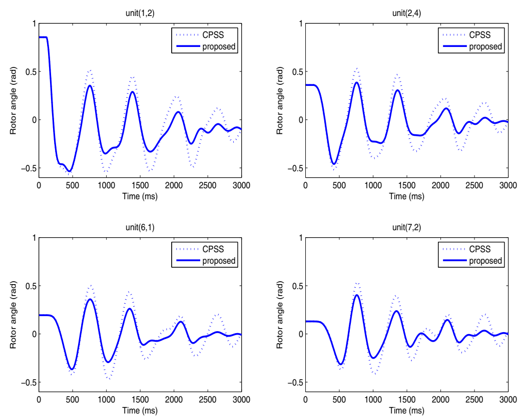

Fig. 10. Rotor angle for selected machines before and after applying the proposed modifications of PSS.

A limitation of this controller that it needs the measurement and processing of all machines' speeds, which impose a time delay that limits the action of controllers for the nearby units to the fault location. Another limitation is in the estimation of the time delay of disturbance propagation, which is considered as the time delay between the first peaks of machines' speeds,

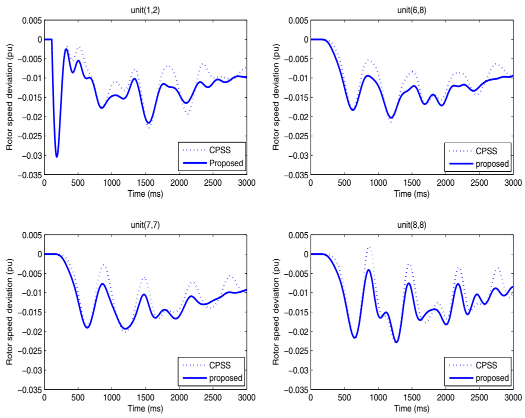

Fig. 11. Rotor speed deviation for selected machines before and after applying the proposed modifications of PSS.

but actually this time delay is not constant between all points of the speed waves, i.e, the time delays between the peaks are larger than the time delays between the tails of the speed waves.

V. Conclusions

In this paper, we have presented a new strategy to dampen the electromechanical wave propagation in power systems equipped with PSS. This strategy is based on information provided by wide-area measurement systems. More specifically, the time delay for disturbance propagation from the fault location to the controlled PSS is exploited to inject an extra damping torque at the appropriate instant. Simulation results presented in this paper show that the application of the new control strategy on PSS leads to improved power system dynamics. However, those results must be verified with more realistic simulation cases, as the power system used in this paper is a regular grid, where all the machine parameters are extracted from the machine data in the literature. Before applying such a strategy to practical power systems, the reliability of such a new control scheme must be studied. In particular, the real benefit of using remote control must be quantified, as this represents an extra complexity with respect to solutions based on local signals only.

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