Decentralized Hierarchical Controller Design for Selective Damping of Inter Area Oscillations Using PMU Signals

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ABSTRACT

This paper deals with the decentralized hierarchical PSS (Power System Stabilizer) controller design to achieve a better damping of specific inter-area oscillations. The two-level decentralized hierarchical structure consists of two PSS controllers. The first level controller is a local PSS controller for each generator to damp local mode in the area where controller is located. This controller uses only local signals as input signals. The local signal comes from the generator at which the controller is located. The secondary level controller is a multivariable decentralized global PSS controller to damp inter-area modes. This controller uses selected suitable wide area PMU (Phasor Measurement Units) signals as inputs. The PMU or global signals are taken from network locations where the oscillations are well observable. The global controller uses only those global input signals in which the assigned single inter-area mode is most observable and is located at a generator that is most effective in controlling the assigned mode. The global controller works mainly in a frequency band given by the natural frequency of the assigned mode. The effectiveness of the resulting hierarchical controller is demonstrated through simulation studies conducted on a test power system.

Key Words: **Two-Level Decentralized Hierarchical Structure, PMU Signals, Selective Damping, Global PSS Controller.**

1. INTRODUCTION

For secure and economical operation of power systems, power system small-signal stability is an important requirement [1]. The deregulation in the electricity market and the extensions of large interconnected power systems led to a situation whereby many tie lines operate near their maximum capacity, especially those connected to areas of high load density. Stressed operating conditions can increase the possibility of inter-area oscillations between different control areas and can even lead to the breakup of the whole system [2]. Weakly damped low frequency inter-area oscillations, inherent in large interconnected power systems during transient conditions, degrade the reliability and performance of such systems. Since power transfers are expected to increase in future, therefore, the damping of inter-area oscillations will decrease [3-4]. The solution for this is to construct new transmission lines [3-4]. However, construction of new power transmission lines is limited

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because of environmental and cost factors [3-4]. The other solution for increasing damping of oscillations is to use heavy high-voltage equipment such as series-compensation. The draw back of this is that the high-voltage equipment is expensive. Therefore, for achieving maximum available transfer capability and improved system security, such kind of system stability control should be used which leads to damping improvement.

The best signal to be used as an input to the controller, for damping the dominant inter-area mode, would be from the location where the oscillations are well observable. In [5] it is reported that the damping of oscillations may be increased with the controller which uses global or remote signals, coming from distant locations of the power system, as its input signals during the design. The global signals contain information about overall network dynamics as opposed to local control signals which do not have enough observability of some of the significant inter-area modes [6].

WAM (Wide Area Measurement) technologies using PMUs can deliver synchronous control signals at high speed. PMUs, deployed at suitable locations on the grid, obtain a coherent picture of the entire network in real time [7]. PMUs measure voltages and currents at different locations of the grid. GPS (Global Positioning System) ensures proper time synchronization among several global signals [8]. The measured global signals are then transmitted via modern telecommunication equipment to the controllers.

In [8], the design of a local decentralized PSS controller, using both local and remote input signals, for selective damping of electromechanical oscillations is presented. This paper presents the design of a local two-level decentralized hierarchical PSS controller for selective damping of inter-area oscillations. The hierarchical control scheme consists of two levels of control. The first level control is a local PSS controller that gives minimum performance of the power system. Second level control is a global PSS controller, using remote PMU signals, that maximizes the performance of local controllers. Simulation studies on a 3-machine test power system are conducted to investigate the effectiveness of proposed controllers during system disturbances.

The remaining paper is organized as follows. Section 2 discusses the structure of the two-level hierarchical control scheme. The design of H_∞-based robust hierarchical PSS controller is described in Section 3. In Section 4, the application results are presented for a dynamic model of three- machine, three-area test power system. Section 5 concludes the paper.

2. TWO-LEVEL DECENTRALIZED HIERARCHICAL CONTROLLER

The two-level decentralized hierarchical control structure consists of two controllers. First level controller is a conventional local PSS controller for each generator to damp local mode in the area where controller is located. The first level local controller uses only local signals as input signals. The local signal is a signal that comes from the generator at which it is located. The secondary level controller is a multivariable decentralized global PSS controller to damp inter-area modes. The secondary level global controller uses selected suitable wide area PMU signals as inputs. The PMU or global signals are taken from network locations where the oscillations are well observable. The total control signal which is fed to the generator is the sum of the control signals of first level local PSS controller and the secondary level global PSS controller. The first level control gives minimum performance of the power system. Second level control enhances the performance of local controllers.

The two-level decentralized hierarchical control structure described above has been applied in this paper for selective damping of inter-area oscillations. In selective damping scheme [8], each of the decentralized global PSS controllers is designed separately for each of the inter-area modes of interest. Thus, each global PSS receives the most suitable measurement information about the inter-area oscillations to be damped. The global PSS controller uses only those remote PMU input signals in which the assigned single inter-area mode is most observable. The global controller is located at a generator that is most effective in controlling the assigned mode. The global controller works mainly in a frequency band given by the natural frequency of the assigned mode. The architecture used in this work is shown in Fig. 1. The hierarchical controllers are acting on the reference inputs of the AVRs (Automatic Voltage Regulators). Inputs of global PSS controller are the PMU signals which come from the complete system [7].

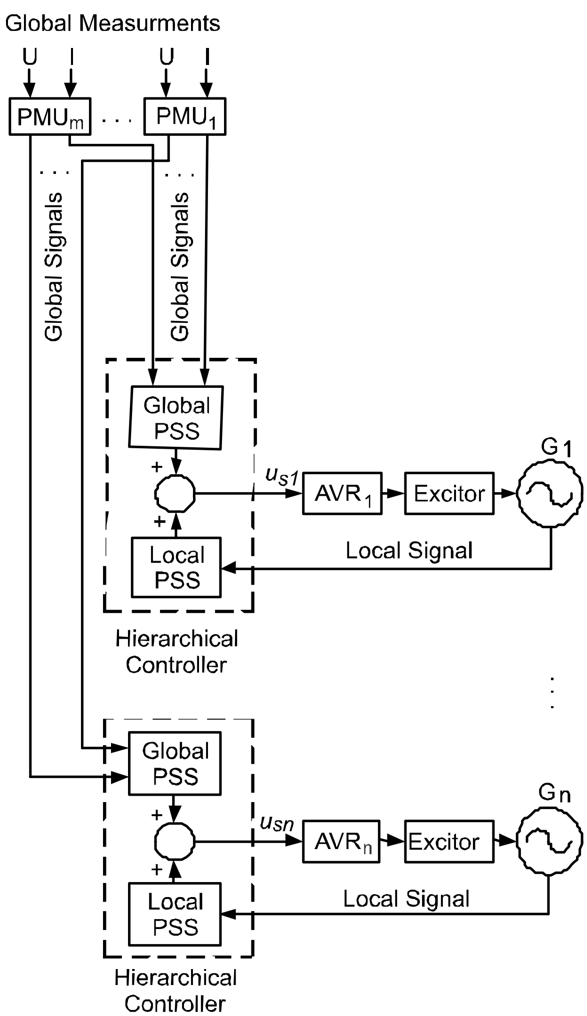

FIG. 1. MULTI-MACHINE POWER SYSTEM WITH DECENTRALIZED HIERARCHICAL CONTROLLER

3. DESIGN OF DECENTRALIZED HIERARCHICAL PSS CONTROLLERS

The general structure of the i^{th}-generator together with the decentralized hierarchical controller in a multi-machine power system is shown in Fig. 2. It has been assumed that each generator in the multi-machine power system is equipped with local PSS controller. Local input signal of the local PSS controller is considered to be deviation of rotor speed ($\Delta\omega_i$). Now, the objective is to design global PSS controller of decentralized hierarchical controller for the i^{th}-generator in the multi-machine power system.

The decentralized hierarchical controller is merged into the multi-machine power system to form a closed loop system. The closed loop system can be described by the following equations [9]:

$$\dot{\mathbf{x}}\mathrm{cls}(t) = \mathbf{A}_{\mathrm{cls}}\mathbf{x}_{\mathrm{cls}}(t) + \mathbf{B}_{\mathrm{cls}}\mathbf{w}(t) \tag{1}$$

$$\mathbf{z}(t) = C_{cls}\mathbf{x}_{cls}(t) + \mathbf{D}_{cls}\mathbf{w}(t) \tag{2}$$

where, $\mathbf{x}_{cls}(t) = [\mathbf{x}^T_{ol}(t)\ \mathbf{x}^T_{gc}(t)]^T$ is the augmented state vector for the closed-loop system, $\mathbf{x}_{ol}(t)$ is state vector of open-loop system (plant and the local PSS controller) augmented by weighting functions of global PSS controller of hierarchical controller, and $\mathbf{x}_{gc}(t)$ is state vector of global PSS controller. Now, an H_∞-based global controller for the open loop system can be obtained by finding the controller matrix, in Equestions (1) and (2), such that the controller matrix internally stabilizes closed loop transfer functions $\mathbf{H}_{zw}(s)$ (Fig. 3). The controller matrix should also satisfy an H_∞ norm bound condition on $\mathbf{H}_{zw}(s) = \mathbf{C}_{cls}(sI-\mathbf{A}_{cls})^{-1}\mathbf{B}_{cls}$ from disturbance $\mathbf{w}(t)$ to the regulated outputs $\mathbf{z}(t)$ [10]. This means that for a certain prescribed disturbance attenuation level $\gamma > 0, \|\mathbf{H}_{\mathbf{zw}}(s)\|_\infty < \gamma$.

4. APPLICATION RESULTS

4.1 Demonstration Model

Three-machine, three-area test power system [8], shown in Fig. 4, has been chosen to apply and show the effectiveness of proposed decentralized hierarchical controller design approach for better selective damping of inter-area oscillations. The considered test power system has three equivalent synchronous generators, each representing one of the three areas. Detailed information about this test system is given in [8]. The i^{th}-generator and the n^{th}_{ci}-order global PSS controller in a multi-machine power system shown in Fig. 2 is considered for all simulation studies and the global PSS controller design.

The profile of two most weakly damped inter-area modes of oscillation, for the nominal power flow solution of the test system, without PSS controllers and with local PSS controllers located in the system only, is given in Table 1 [8]. The results provided in the table indicate that local PSS controllers have not significant effect on inter-area modes 1 and 2.

Hashmani, A.A., et. al., [9] have carried out the selection of suitable remote input signals and locations of local decentralized PSS controllers, to be designed to damp out the two most weakly damped inter-area modes in the considered three-machine, three-area test system shown in Fig. 4. It has been found in [9] that current flowing through transmission line connected between buses 5 and 6 (I_{56}) is suitable as a global input signal for the global PSS controller to be designed to damp inter-area mode 1 and generator G1 is highly effective and suitable as the location of the designed global PSS controller. It has also been found in [9] that θ_{v5} is suitable as a global input signal for

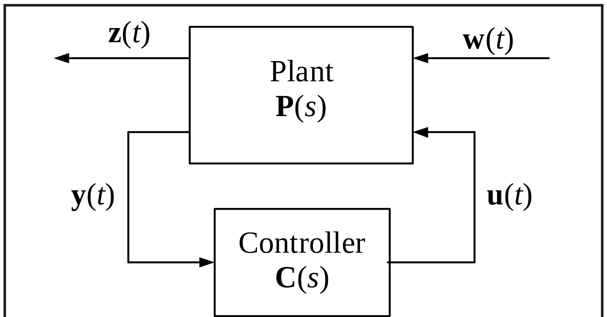

FIG. 3. INTERCONNECTED SYSTEM REPRESENTATION BY LFT FRAMEWORK

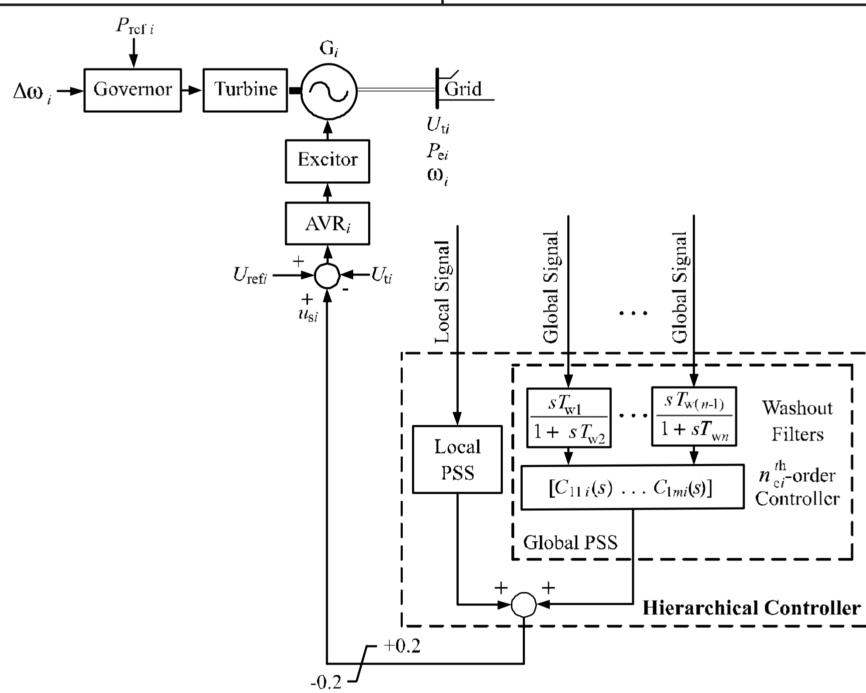

FIG. 2. GENERAL STRUCTURE OF THE i^{th}-GENERATOR TOGETHER WITH DECENTRALIZED HIERARCHICAL CONTROLLER IN A MULTI-MACHINE POWER SYSTEM

the global PSS controller to be designed to damp inter-area mode 2 and generator G3 is highly effective and suitable as the location of the designed global PSS controller.

Thus, for the design of global controller for inter-area mode 1, we have $\mathbf{y}(t) = I_{56}(t)$ and $\mathbf{z}(t) = [I_{56}(t)\ u_{sG1}(t)]^T$ and for the design of global controller for inter-area mode 2, we have $\mathbf{y}(t) = \theta_{v5}(t)$ and $\mathbf{z}(t) = [\theta_{v5}(t)\ u_{sG3}(t)]^T$. The design procedure stated in Section 3 will be followed for the design of global controllers.

4.2 Design of Controllers

For the design of global controllers, sequential design method [8] is used. The description of two possible sequential designs is given in the following subsections. Note that first control loop consists of plant and the hierarchical controller 1 (global PSS controller designed for inter-area mode 1) located at G1. The second control loop consists of plant and the hierarchical controller 2 (global PSS controller designed for inter-area mode 2) located at G3.

4.2.1 First Sequential Design

First sequential design has two steps. The steps are given as follows:

(i) Global PSS controller for inter-area mode 1 is designed first by keeping the second control loop open;

(ii) Global PSS controller for the inter-area mode 2 is then designed by keeping the first control loop closed, i.e. with already designed hierarchical controller 1 located at generator G1 in the test system.

The global PSS controller for inter-area mode 1 is designed first by keeping the second control loop closed. The designed global PSS controller for the inter-area mode 1 is given as follows:

$$\mathbf{C}_{11}(s) = 19.312\frac{(1+s\,0.0324)(1+\ s1.0918)}{(1+s\,0.1974)(1+s\,0.1353)}$$

Table 2 provides the profile of two weakest damped inter-area modes of the test system with hierarchical controller

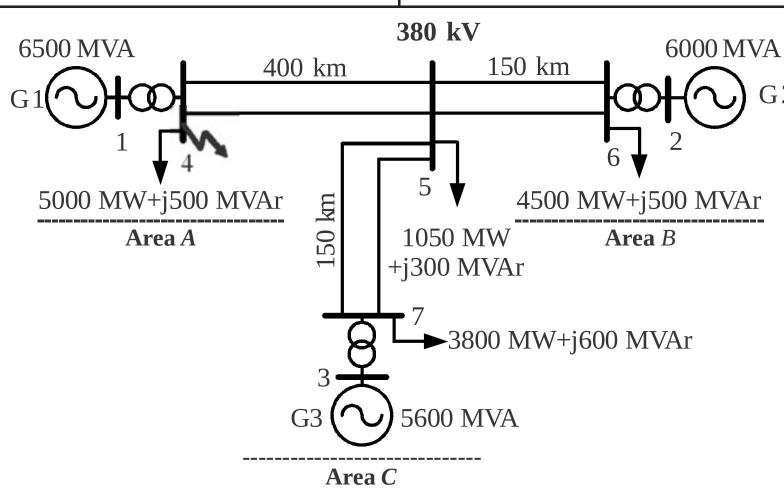

FIG. 4. THREE-MACHINE, THREE-AREA TEST POWER SYSTEM

TABLE 1. WEAKLY DAMPED INTER-AREA MODES OF TEST SYSTEM

Mode No.	Without PSS Controllers			With Local PSS Controllers Only		
	Inter-Area Modes	ζ (%)	Frequency (Hz)	Inter-Area Modes	ζ (%)	Frequency (Hz)
1.	-0.4070+4.2293	9.58	0.67	-0.4071+4.2293	9.98	0.67
2.	-0.3810+5.8765	6.47	0.92	-0.3810+5.8765	7.07	0.92

1 located in the system only and with both hierarchical controllers 1 and 2 located in the system. The results show that with the designed global PSS controller for inter-area mode 1 added to the already installed local PSS controller (hierarchical controller 1), the damping of inter-area mode 1 has increased significantly.

The global PSS controller for inter-area mode 2 is now designed by keeping the first control loop closed, i.e. with already designed hierarchical controller 1 located at generator G1 in the test system. The designed global PSS controller for the inter-area mode 2 is given as follows:

$$\mathbf{C}_{22}(s) = 10.49\frac{(1+s0.2169)(1+s\,2.6702)}{(1+s\,0.1274)(1+s\,0.1853)}$$

The results given in the Table 2 indicate that with the designed global PSS controller for inter-area mode 1 added to the already installed local PSS controller (hierarchical controller 2), the damping of inter-area mode 2 has increased significantly while there is little effect on the damping of inter-area mode 1.

4.2.2 Second Sequential Design

Second sequential design has also two steps. The steps are given as follows:

(i) Global PSS controller for inter-area mode 2 is designed first by keeping the first control loop open.

(ii) Global PSS controller for the inter-area mode 1 is then designed by keeping the second control loop closed, i.e with already designed hierarchical controller 2 (global PSS controller for inter-area mode 2) located at generator G3 in the test system.

Table 3 provides the profile of two weakest damped inter-area modes of the test system with the hierarchical controllers designed for inter-area modes 2 and 1 located in the system.

It is evident from the results, provided in Tables 2-3 that the damping of inter-area modes 1 and 2 has enhanced more in the second sequential design than that in the first one. Thus, it can be concluded that second sequential design is better than the first one for the test system under consideration.

4.3 Time-Domain Simulation Results

For simulating the behavior of the system to large disturbances, a balanced three-phase fault, for the duration of 300 ms, is applied at bus 6 in the considered test power system. The behavior of deviation of real electrical power delivered by generator G2 ($\Delta P_{G2}(t)$), with local PSS controllers only, with the hierarchical controller 1 (designed during second sequential design) only and with both hierarchical controllers 1 and 2 (designed during second sequential design) located in the system, is shown in Fig. 5. Fig. 5 shows that response of $\Delta P_{G2}(t)$ with only

TABLE 2. WEAKLY DAMPED INTER-AREA MODES OF TEST SYSTEM

Mode No.	With Hierarchical Controller 1			With Hierarchical Controllers 1 and 2		
	Inter-Area Modes	ζ (%)	Frequency (Hz)	Inter-Area Modes	ζ (%)	Frequency (Hz)
1.	-1.0070+4.2295	31.37	0.68	-1.1070+4.2295	33.37	0.68
2.	-0.3890+5.8765	7.77	0.92	-1.6290+5.8065	39.77	0.91

TABLE 3. WEAKLY DAMPED INTER-AREA MODES OF TEST SYSTEM

Mode No.	With Hierarchical Controller 2			With Hierarchical Controllers 2 and 1		
	Inter-Area Modes	ζ (%)	Frequency (Hz)	Inter-Area Modes	ζ (%)	Frequency (Hz)
1.	-0.4170+4.2293	9.98	0.67	-0.4170+4.0293	41.08	0.70
2.	-1.2610+5.3765	42.42	0.89	-1.2610+5.3765	42.42	0.89

local PSS controllers is oscillatory. The figure indicates that the damping of the response improves when proposed hierarchical controller 1 was used. As global PSS controller of the hierarchical controller 1 was designed for inter-area mode 1 only, therefore the response of $\Delta P_{G2}(t)$ in Fig. 5 is still oscillatory. Fig. 5 also shows that the response is well damped with the hierarchical controllers 1 and 2 located in the system. Thus, the proposed hierarchical controllers improve the performance of local PSS controllers and enhance small-signal stability.

5. CONCLUSION

The design of a local two-level decentralized hierarchical PSS controller for selective damping of inter-area oscillations, proposed in this paper, is applied on a three-machine, three-area test power system. The first level control is a local PSS controller while the second level control is a global PSS controller. Two decentralized hierarchical controllers have been designed. Hierarchical controller (global controller) for an assigned single inter-area mode is designed first by keeping the other control loop open. Hierarchical controller (global controller) for the other assigned single inter-area mode is then designed by keeping the first control loop closed, i.e. with already designed hierarchical controller for the first assigned single inter-area mode located in the test system. The global input signals, used by the global controllers, have been selected in a way that the assigned modes are highly observable in the input signals of the corresponding controllers. The generators which are highly effective in controlling the assigned modes have been selected as the locations of the hierarchical controllers. The design of global controllers has been carried out designed in such a way that each global controller is effective only in the natural frequency of its assigned mode. The designed hierarchical controllers, thus, damp only their corresponding assigned modes. The nonlinear simulation results show that the first level control, i.e., local controller gives minimum performance of the power system while, the second level control, i.e., global controller, using remote PMU signals, maximizes the performance of local controllers.

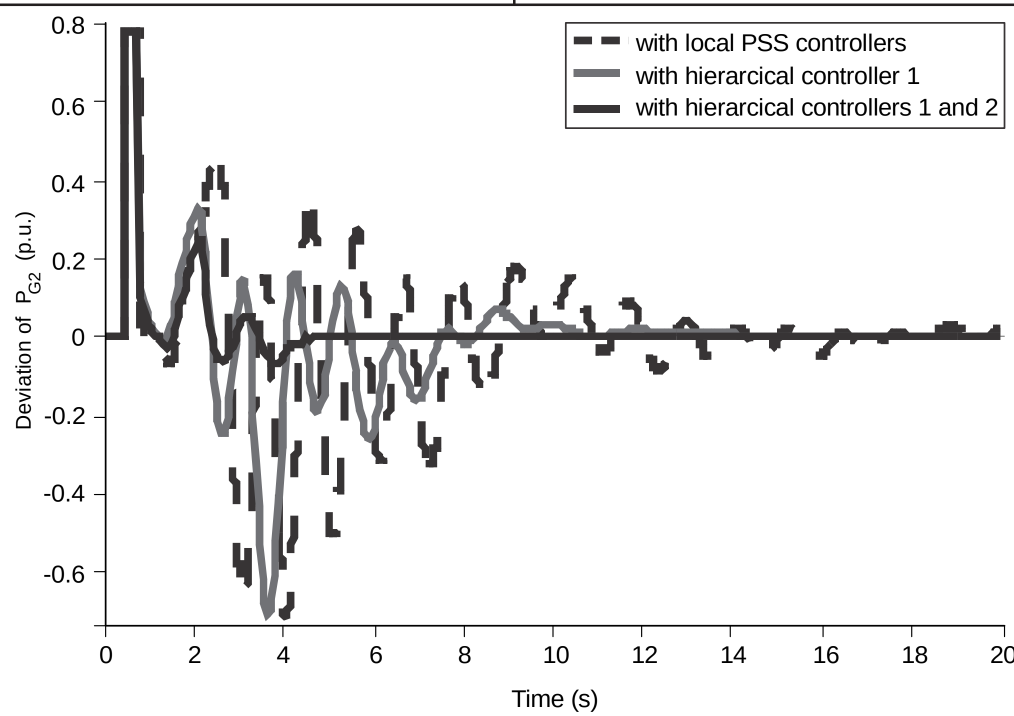

FIG. 5. DEVIATION OF $P_{G2}(t)$ ($\Delta P_{G2}(t)$) FOLLOWING A THREE-PHASE FAULT AT BUS 6 IN THE TEST SYSTEM

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