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PERFORMANCE EVALUATION FOR DAMPING CONTROLLERS OF POWER SYSTEMS BASED ON MULTI-AGENT MODELS*

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Abstract This paper proposes a multi-layer multi-agent model for the performance evaluation of power systems, which is different from the existing multi-agent ones. To describe the impact of the structure of the networked power system, the proposed model consists of three kinds of agents that form three layers: control agents such as the generators and associated controllers, information agents to exchange the information based on the wide area measurement system (WAMS) or transmit control signals to the power system stabilizers (PSSs), and network-node agents such as the generation nodes and load nodes connected with transmission lines. An optimal index is presented to evaluate the performance of damping controllers to the system's inter-area oscillation with respect to the information-layer topology. Then, the authors show that the inter-area information exchange is more powerful than the exchange within a given area to control the inter-area low frequency oscillation based on simulation analysis.

Key words Damping controller, inter-area oscillation, multi-layer multi-agent system, power system.

1 Introduction

For the past decades, electric power systems have seen a great change in their infrastructures and control mechanism. The large-scale power systems have gradually become geographically owned by several regional investors and these regional subsystems are interconnected together through tie-lines. Hence, the supervision and management of subsystems are naturally distributed, and the conventional centralized control systems, which are highly fragile to failures as the whole system relies on the single decision-making system, tend to be inadequate in practice. Nowadays, the operation of power system requires a large number of regional control systems to work jointly to meet the overall objectives. Although each regional control system only has local and limited information, the engineering goals of the whole systems can be achieved on the basis of the satisfactory coordination of all regional systems.

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A number of techniques have been developed and applied in this scenario[1], and multi-agent systems (MAS) with inherent decentralized properties as pointed out in [2–3] have become a focal point. Due to the distributed structure of deregulated power system, feasibilities of the application of MAS were analyzed in current energy management system[3−4], while MAS models were studied to ensure reliable deregulated power system and its operations[5−6]. MAS was also introduced to investigate autonomous and distributed protective devices[7−8], related fault diagnosis systems[9], and condition monitoring system[10]. Furthermore, due to the decentralized structure of control components, MAS was applied to power system voltage stability[12−13], restoration[14−15], state estimation[16], substation automation[17], power system vulnerability assessment[18], and damping controller[19−21]. However, there have not been any theoretic frameworks or effective approaches in the control of deregulated electric power system.

In power systems, the stability of electro-mechanical oscillations between interconnected synchronous generators is required to guarantee the system operation. The oscillations of one or more generators within a specific area are called local modes, while those associated with groups of generators in different areas oscillating against each other are called inter-area modes[22]. These oscillations, especially inter-area oscillations, are directly related to the whole system performance and critical analysis. To provide damping to system oscillations, the distributed components, power system stabilizers (PSSs), especially with local rotor speed as input, have been used for many years. Local PSSs are effective in damping local modes, but do not work well in damping inter-area modes that are not so easily controlled and observed as the local modes. In recent years, the distributed instrumentation technology using accurate phasor measurement units (PMUs)[23−24] has been developed. It is found that if remote signals from distant areas are applicable to local-mode controller design, system performance can be much improved[19−21,25−26]. However, the essential problems such as why the local PSS is limited and why and how the PSS with PMU signal could well damp the inter-area oscillation are not clear and still under investigation.

In this paper, we propose a multi-agent model to give a performance evaluation of damping controller for oscillations of power systems from the topology-based viewpoint. In this way, the power system is regarded as a three-layer multi-agent system. The first layer is the control layer, including the generators and its associated controls such as excitation systems and PSSs, interconnected to the generation node. The second layer is the transmission network layer, which represents the power network formed by the interconnection of the generation nodes and load nodes with transmission lines. The third is the information layer, composed of the information agents that exchange the information via the WAMS system and send the control signals to the PSSs. In fact, our multi-agent model is different from the existing ones in power systems[19−21], since we emphasize that the PSS with PMU signal (or the introduction of the remote signals) implies the change of information-flow structure for the power system. To our knowledge, this is the first model to study the damping controller from the performance viewpoint based on topologies of a specific layer (that is, information-layer in this paper).

For the performance evaluation of the control of inter-area oscillations, an agent-based performance index, for the minimum distance of the eigenvalues with respect to the imaginary axis under a certain information-layer topology, is given for various information-layer topologies. In other words, the optimal index provides an impact analysis of information-layer structures on the damping performance. Therefore, the proposed model along with its associated index could help us select the input signals for the damping controllers to damp the power system low frequency (inter-area) oscillation.

The paper is organized as follows. In Section 2, a multi-layer multi-agent model for power systems is presented, while in Section 3, the performance index is formulated for the performance evaluation and optimization of the considered system. Then, in Section 4, simulation results using Genetic Algorithm (GA)[27] show the inter-area information flows play a key role in the control of inter-area oscillations. Finally, the conclusions are given in Section 5.

2 Multi-Agent Models for Power System

In this section, we introduce a new multi-agent model for performance analysis of power systems, which contains not only different components such as generators and their associated excitation systems, transmission lines, and the loads, but also advanced information system to collect and exchange the information.

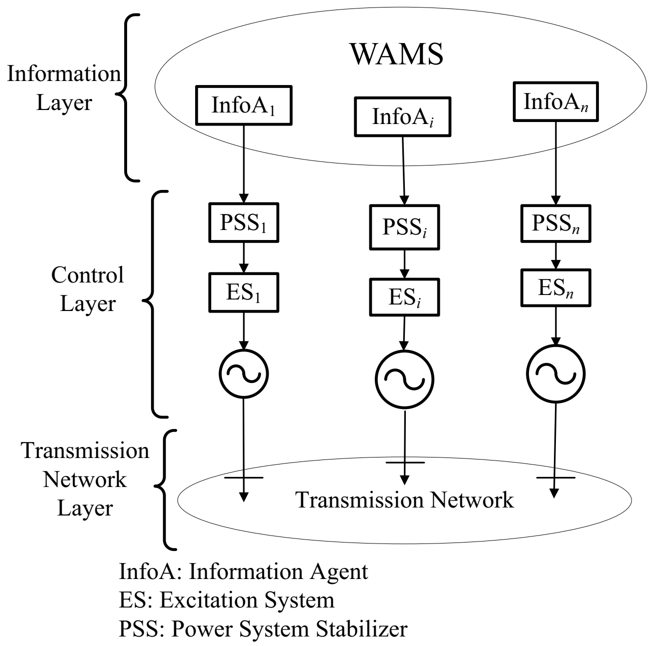

Figure 1 Multi-layer multi-agent structure for damping analysis

In the analysis and control of system oscillation, the generator and its associated excitation system, power system stabilizers plays vital roles. With the introduction of PMU in the last decade, the information system also becomes more important to the power system oscillation. Considering the components and their important roles in oscillation, there are three main kinds of agents, based on the function of the components, in power systems. The first are the network-node agents, which contains generation-node agents, load-node agents, interconnected with the transmission lines. And the second are the control agents, which could be the generators and the associated excitation systems or power system stabilizers. The third are the information agents, which afford the different signals to the control agents.

The above agents form a three-layer multi-agent system as shown in Figure 1. The control agents, which contains the generators locally controlled by their excitation systems and PSSs, connected to the generation node, form the control layer, while the generation-node agents and the load-node agents, connected with the transmission lines, form the transmission network layer of multi-agent system. Furthermore, the information agents, with the information flow among them, form the third layer–information layer, with the aid of the WAMS technology.

Clearly, the information-layer structure/topology and transmission-network structure play an important role in the performance of the whole system. Here, this paper only focuses on the impact of the information-layer structure.

To be strict, consider a power system consisting of n generators and m nodes. With the multi-layer multi-agent structure shown in Figure 1, the three layers are described as follows.

• Control layer

In the control layer, the dynamics of the i-th generator can be written as:

$$\begin{aligned}
&\dot{\delta}_i = 2\pi f_B(\omega_i - 1),\\
&2H_i\dot{\omega}_i = P_{mi} - D_i(\omega_i - 1) - (E''_{qi}i_{qi} + E''_{di}i_{di} - (X''_{di} - X''_{qi})i_{di}i_{qi}),\\
&T'_{d0i}\dot{E}'_{qi} = E_{fi} - E'_{qi} - (X_{di} - X'_{di})\Big(1 - \frac{T''_{d0i}}{T'_{d0i}}\frac{X''_{di}}{X'_{di}}\Big)i_{di},\\
&T'_{q0i}\dot{E}'_{di} = -E'_{di} - (X_{qi} - X'_{qi})\Big(1 - \frac{T''_{q0i}}{T'_{q0i}}\frac{X''_{qi}}{X'_{qi}}\Big)i_{qi},\\
&T''_{d0i}\dot{E}''_{qi} = -E''_{qi} + E'_{qi} - \Big[(X'_{di} - X''_{di}) - \frac{T''_{d0i}}{T'_{d0i}}\frac{X''_{di}}{X'_{di}}(X_{di} - X'_{di})\Big]i_{di},\\
&T''_{q0i}\dot{E}''_{di} = -E''_{di} + E'_{qi} - \Big[(X'_{qi} - X''_{qi}) - \frac{T''_{q0i}}{T'_{q0i}}\frac{X''_{qi}}{X'_{qi}}(X_{qi} - X'_{qi})\Big]i_{qi},
\end{aligned} \tag{1}$$

where δ_i and ω_i are the rotor angle and rotor speed of generator i, $E'_{di}(E''_{di})$ and $E'_{qi}(E''_{qi})$ are the transient (sub-transient) voltage of generator i of d-axis and q-axis, respectively. The D_i and H_i are damping ratios and machine inertia of generator i, P_{ei} and P_{mi} are the electrical and mechanical power at generator i, respectively. $\omega_0 = 2\pi f_B$. X_{di}, X'_{di}, X''_{di} and X_{qi}, X'_{qi}, X''_{qi} are the synchronous reactance, transient reactance, and sub-transient reactance of d-axis and q-axis of generator i. T'_{d0i} (or T''_{d0i}) and T'_{q0i} (or T''_{q0i}) are the open circuit transient (or sub-transient) time constants of d-axis and q-axis of generator i. x_{li} is the leakage reactance of generator i. E_{fi} is the field voltage, which is determined by the excitation system. The relationships between the voltages (E_{qi} and E_{di}) and currents (i_{di} and i_{qi}) are given as

$$\begin{aligned}
0 &= E_{qi} + r_{ai}i_{qi} - E''_{qi} + (x''_{di} - x_{li})i_{di},\\
0 &= E_{di} + r_{ai}i_{di} - E''_{di} - (x''_{qi} - x_{li})i_{qi},
\end{aligned} \tag{2}$$

where x_{li} is the leakage reactance of generator i.

The interface between the generator i and the corresponding generation node in the transmission network layer is described by the following equations:

$$\begin{bmatrix} U_{xi} \\ U_{yi} \end{bmatrix} = \begin{bmatrix} \sin\delta_i & \cos\delta_i \\ -\cos\delta_i & \sin\delta_i \end{bmatrix} \begin{bmatrix} E_{di} \\ E_{qi} \end{bmatrix}, \tag{3}$$

$$\begin{bmatrix} I_{xi} \\ I_{yi} \end{bmatrix} = \begin{bmatrix} \sin\delta_i & \cos\delta_i \\ -\cos\delta_i & \sin\delta_i \end{bmatrix} \begin{bmatrix} I_{di} \\ I_{qi} \end{bmatrix}. \tag{4}$$

Furthermore, for each generator, the field voltage, $E_{fi} = E_{fi}(x_{Ei})$ is determined by the associated excitation system, i.e., one kind of control agents. Although the excitation system has different types, in general, it can be expressed as

$$\dot{x}_{Ei} = f_{Ei}(x_{Ei}, x_{Gi}) + g(x_{Ei})U_{\text{refi}}, \tag{5}$$

where x_{Ei} is the state of the excitation system i, x_{Gi} is the state of the generators, $U_{\text{refi}} = U_{\text{refi}}(x_{\text{PSSi}})$ is the signal determined by the control agent system, PSS (maybe with different types). Also, in general, the control agent PSS could be described as

$$\dot{x}_{\text{PSSi}} = f_{\text{PSSi}}(x_{\text{PSSi}}) + g(x_{\text{PSSi}})u_i, \tag{6}$$

where u_i is the input signal given by the information agent i, and it could contain local signals and global signals.

• Information layer

The information layer, which provides the input signal (information) to the control agent, could be described as follows:

$$u_i = u_i(y_i), \quad i = 1, 2, \cdots, n, \tag{7}$$

where y_i is the input signal at control agent i, and it could be described as follows:

$$y_i = y_i(x_1, x_2, \cdots, x_j, \cdots, x_n), \quad i = 1, 2, \cdots, n, \tag{8}$$

where x_i is the state of the generator agent i, x_i is the state of the generator agent i and its associated control agents, i.e., $x_i = (\delta_i,\ \omega_i,\ E'_{qi},\ E'_{di},\ E''_{qi},\ E''_{di},\ x_{Ei}^{\mathrm{T}},\ x_{\text{PSSi}}^{\mathrm{T}})^{\mathrm{T}}$. The information flow in the information layer are implicitly representation in (8).

• Transmission network layer

The transmission network is modeled as the following linear equation

$$I = YU, \tag{9}$$

where $Y = (G_{ij} + jB_{ij})_{m\times m}$ is the network admittance matrix, $I = (I_1, I_2, \cdots, I_m)^{\mathrm{T}}$ and $U = (U_1, U_2, \cdots, U_m)^{\mathrm{T}}$, I_i and U_i are the current and voltage at the node i, respectively, and $I_i = I_{xi} + jI_{yi}$, $U_i = U_{xi} + jU_{yi}$.

3 Performance of Damping Controllers

In this section, the general formulation of multi-layer multi-agent system for the linear system is given to evaluate the performance of the damping controllers according to different structures of information layer.

For simplicity, the multi-layer multi-agent system can be linearized around the operating points, and given in the following form:

$$\left.\begin{aligned} &\dot{x}_i = A_{ii}x_i + \sum_{j\neq i} A_{ij}x_j + B_i u_i, \\ &y_i = \begin{pmatrix} y_{Li} \\ y_{Gi} \end{pmatrix} = \begin{pmatrix} C_{Li} \\ C_{Gi} \end{pmatrix} x = C_i x, \end{aligned}\right. \quad i = 1, 2, \cdots, n, \tag{10}$$

where x_i is the state of the generator agent i and its associated control agents, i.e., $x_i = (\delta_i, \omega_i, E'_{qi}, E'_{di}, E''_{qi}, E''_{di}, x_{Ei}^{\mathrm{T}}, x_{\text{PSSi}}^{\mathrm{T}})^{\mathrm{T}}$, u_i is the signal, which is directly applied to the control agent i, $y_i = (y_{Li}^{\mathrm{T}}, y_{Gi}^{\mathrm{T}},)^{\mathrm{T}}$ is the output signal, which is sent to the control agent by the information agent i, just as mentioned in Section 2. The output signals are divided into two types: one is the local signals, y_{Li}, measured by the information agent i, and the other is the global signals, y_{Gi}, obtained by information agent i via the WAMS system in Figure 1. Equivalently, the output signal could be described as

$$y_{Li} = \sum_{k=1}^{n} C_{Li,k}x_k, \quad y_{Gi} = \sum_{k=1}^{n} C_{Gi,k}x_k, \tag{11}$$

where $C_{Li} = (C_{Li,1}, \cdots, C_{Li,k}, \cdots, C_{Li,n})$, $C_{Gi} = (C_{Gi,1}, \cdots, C_{Gi,k}, \cdots, C_{Gi,n})$ are the observable matrix for local and global signal.

The information-layer structure (or the interconnection of information agents in Figure 1) is identified by the observable matrix for global signal $C_{Gi} = (C_{Gi,1}, \cdots, C_{Gi,k}, \cdots, C_{Gi,n})$. Specifically, the connection of information agent i with information agent j is specified by the non zeros of the matrix $C_{Gi,j}$. Furthermore, as usual, the graph representation for the interconnection of the information agents (or the information layer structure) can be described as the adjacent matrix $G = (g_{ij})_{n\times n}$, with the elements defined as

$$g_{ij} = \mathrm{sgn}(||C_{Gi,j}||), \quad g_{ii} = 0, \tag{12}$$

where $||\cdot||$ is the matrix Euclidean norm, $\mathrm{sgn}(\cdot)$ is the sign function. Clearly, G associated with the information layer is a directed graph.

The above multi-agent system, shown in Figure 1, can be expressed as follows:

$$\begin{aligned} &\dot{x} = A^N x + B^N u, \quad y = C^N x, \\ &u = K^N y, \end{aligned} \tag{13}$$

where $A^N = (A_{ij})_{n\times n}$, $B^N = \mathrm{diag}(B_1, B_2, \cdots, B_n)$, $C^N = (C_1^{\mathrm{T}}, C_2^{\mathrm{T}}, \cdots, C_n^{\mathrm{T}})^{\mathrm{T}}$, $K^N = \mathrm{diag}(K_1, K_2, \cdots, K_n)$. System (13) is different from the traditional decentralized control formulation because it explicitly distinguishes the local and global signal in the matrix C^N. Note that the structure of transmission network layer is described in (10).

Clearly, the stability of the synchronous and oscillation mode of the multi-agent system is totally determined by the eigenvalues of the matrix

$$A_{K^N} = (A^N + B^N K^N C^N). \tag{14}$$

Let $\sigma_k(A_{K^N})$ $(k = 1, 2, \cdots, n_x)$ be the eigenvalue of the matrix A_{K^N}, and the order of the eigenvalues satisfying the inequality

$$\mathrm{Re}(\sigma_k(A_{K^N})) \geq \mathrm{Re}(\sigma_{k+1}(A_{K^N})). \tag{15}$$

The multi-layer multi-agent power system (13) and (14) have two zero eigenvalues: one is related to the relative position (angle), and the other is related to the uniform damping (i.e, $D_i/H_i = c_o$). Considering the above two zero eigenvalues, the stability of the multi-agent system synchronous with the controller K^N is determined by

$$I_{K^N} = \max\left\{\{\mathrm{Re}\sigma_i(A_{K^N}),\, i = 1, 2, \cdots, n_x\}\backslash\{0, 0\}\right\}. \tag{16}$$

In fact, I_{K^N} is the minimal distance of the eigenvalues (excluding the zeros eigenvalue corresponding to the relative position and uniform damping) with respect to the imaginary axis with certain control $u = K^N x$ under fixed information layer structure.

Furthermore, I_{K^N} is not only the criterion for the stability of synchronous, but also the upper limit of the damping of the oscillation mode with the controller K^N. Then, the performance of different controllers with the same information-layer structure could be evaluated by the index given as

$$I_G = \min_{K^N \in G^N} \{I_{K^N}\}, \tag{17}$$

or equivalently,

$$I_G = \min_{K^N \in G^N} \left\{\max\left\{\{\mathrm{Re}\sigma_i(A_{K^N}),\, i = 1, 2, \cdots, n_x\}\backslash\{0, 0\}\right\}\right\}, \tag{18}$$

where G^N represents the set of all possible feedback control under the information layer with topology G. In other words, I_G is a performance index for the damping controller of multi-agent system with a given structure G.

Remark 3.1 In the case of non-uniform damping, the system (13) only has one zero eigenvalue, and then the index should be

$$I_{K^N} = \max\left\{\{\mathrm{Re}\sigma_i(A_{K^N}),\, i = 1, 2, \cdots, n_x\}\backslash\{0\}\right\}. \tag{19}$$

Remark 3.2 Note that the damping controller is neither full state feedback nor the dynamic output feedback. With static output feedback, the system may not be stabilized, i.e., the index I_G may be greater than zero, though the controllability condition is satisfied. In fact, if, for a information layer topology G_0, there exist fixed modes given as follows:

$$\Lambda(G_0) = \Lambda(A, B^N, C^N) = \bigcap_{K^N} \sigma(A + B^N K^N C^N),$$

then the real part of one fixed mode may be the optimal solution to the performance index, namely,

$$I_{G_0} \geq \max\{\mathrm{Re}\sigma_j, \sigma_j \in \Lambda(G_0)\}.$$

However, in the case of no fixed mode, the system could be assigned pole arbitrary via the dynamic output feedback (instead of conventional static output feedback). Therefore, the performance with the static output feedback may be much improved using dynamic output feedback based on the usage of information layer.

4 Simulation Results

The simulation results are based on a four-generator two-area system, which is a widely used benchmark system in inter-area oscillation analysis[22], as shown in Figure 2.

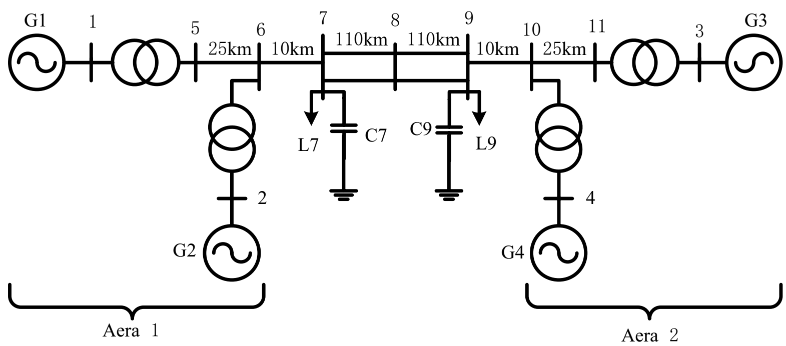

Figure 2 Four-generator two-area system

The proposed index (17) is related to an optimal problem involving the eigenvalue computation, and discontinuous maximizing operation, and certainly a totally nonlinear programming, which is very hard to be analyzed in a strict mathematical way. In this paper, we use Genetic Algorithm[27] to handle index (17) to obtain the "optimal" solutions.

The excitation system of each generator is briefly represented by first-order system, as shown in Figure 3, while the power system stabilizer connected to each excitation system of the generator is shown in Figure 4.

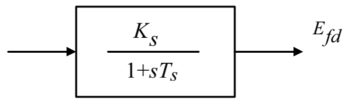

Figure 3 Simple excitation system model block diagram

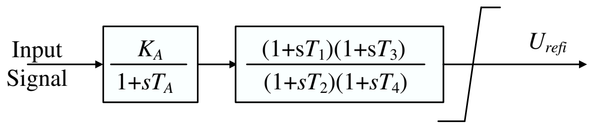

Figure 4 Power system stabilizer model block diagram

To the power system stabilizer, the input signals could be the electric powers, the rotor speeds, the rotor angles, or the signals obtained with dynamic transformation of rotor speed. In our simulation, we only select the rotor angle and speed signals, i.e., δ_i, ω_i, as the local/global signal by the PMU technology[25].

The parameters used in the control agents are listed as follows:

$$K_s = 200, \quad T_s = 0.01, \quad K_A = 300, \quad T_A = 200,$$
$$T_1 = 0.06, \quad T_2 = 0.04, \quad T_3 = 0.08, \quad T_4 = 0.04.$$

Geographically, in this system, the information links within the area, that is, the link between generators 1 and 2, and links between generators 3 and 4 are local-area link, and the information links are the ones between generator 1 (or 2) to generator 3 (or 4) are inter-area links.

In this problem, we basically have six types of information layer topology. Type I (corresponding to the non-connection between any two different information agents) and type VI (corresponding to the full connection between any two different information agents) are trivial and not practical. The other four types of information-flow topologies are shown in Figure 5.

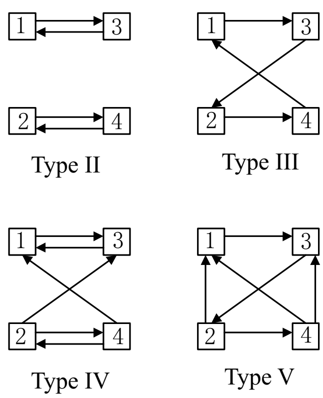

Figure 5 Different information-flow(WAMS system) topologies

The performance of damping controllers with different information-layer topologies and signals (i.e., with the angle information, or with the speed information, or with the angle & speed information together) is obtained with GA as shown in Table 1, where $I_{G\omega}(I_{G\delta}/I_{G\delta\omega})$ represents the performance with angle (speed/angle & speed) information.

Table 1 Performance of different information-layer topologies

Information Layer Structure	$I_{G\omega}$	$I_{G\delta}$	$I_{G\delta\omega}$
Type I (Self connected)	-0.0507	-0.0686	-0.0720
Type II	-0.0524	-0.0748	-0.0748
Type III	-0.0524	-0.0748	-0.0748
Type IV	-0.0528	-0.0748	-0.0748
Type V	-0.0525	-0.0748	-0.0748
Type VI (Full connection)	-0.0528	-0.0748	-0.0748

First, we analyze the performance index with the speed information.

Table 1 shows that in the case of type VI (full connection) or type IV, the damping controller is the most effective, and in the case of type V, type III, and type II, the damping controller is less effective. Furthermore, in the case of only self-connected, the damping controller is the least effective. This verifies our "common sense"; roughly speaking, more connections in the information layer imply the better performance of controllers.

It is easy to see that type IV shows almost the same performance as type VI, which is the most effective performance. The differences are the information links between generators 1 and 2, and those between generators 3 and 4. Moreover, type V gains little performance improvement from type III. The difference between type V and III are the information flow from generator 2 to generator 1 and the information flow from generator 4 to generator 3. Furthermore, as the area 1 contains generators 1 and 2 and the area 2 contains generators 3 and 4, the information flows between generators 1 and 2, or those between generators 3 and 4, are the information links within a specific area. Thus, the above comparison shows that the information flows inside an area has little impact on the inter-area oscillations, which agrees with the engineering beliefs.

On the other hand, type IV gains much performance improvement compared with type II. The difference between them is the information flow from generator 2 to generator 3 and that from generator 4 to generator 1. The information flow from generator 2 to generator 3 and that from generator 4 to generator 1 are the inter-area information links. Thus, the inter-area information flow has great impact on the inter-area oscillations, consistent with the engineering "common sense", i.e., the inter-area modes are largely influenced by global states of large areas of the power network[22].

The important role of the inter-area information flows (or the above "common sense") could be further explained with the sensitivity magnitude shown in Table 2, where the element at the table location $(\text{Gen}.i, \omega_{*,j})$ represents the sensitivity magnitude of the inter-area mode with respect to the introduction of the angle difference between i and j to the associated PSS of generator j, i.e., introducing an information link from generator i to generator j, briefly denoted as $(i \to j)$, in the information layer. Table 2 shows that the inter-area links have greater sensitivity magnitude than the local-area links. For example, for generator 3, the sensitivity magnitude obtained by introducing the local-area link $4 \to 3$ is $9.37 * 10^{-5}$, while it is $2.361 * 10^{-4}$ by the inter-area link $1 \to 3$.

Next, we analyze the performance index with angle (angle & speed) information. Table 1 shows that all the types of information-layer topologies with inter-area links can achieve the same performance as the full-connection case. Comparison with type I case shows great improvement of performance with the introduction of inter-area link (or remote signal). Furthermore, Table 1 shows that with the same information layer topology, the information link with angle could achieve better performance than the information link with speed, and the

Table 2 Sensitivity magnitude of inter-area mode w.r.t. relative speed (10^{-3})

Relative Speed	Gen.1	Gen.2	Gen.3	Gen.4
$\omega_{*,1}$	0	0.1204	0.2361	0.1168
$\omega_{*,2}$	0.0669	0	0.1411	0.0388
$\omega_{*,3}$	0.1664	0.1773	0	0.0773
$\omega_{*,4}$	0.1002	0.0594	0.0937	0

information link with angle & speed only improve little performance than the information link with angle. Therefore, the angle signal information links have greater influence on the damping performance than the speed signal information link. This is confirmed with the sensitivity magnitude of the inter-area mode with respect to the introduction of angle difference, shown in Table 3, which is about 10^3 times more than the sensitivity obtained with speed difference.

Table 3 Sensitivity magnitude of inter-area mode w.r.t. relative angle

Relative Angle	Gen.1	Gen.2	Gen.3	Gen.4
$\delta_{*,1}$	0	0.2172	0.0486	0.0112
$\delta_{*,2}$	0.0039	0	0.0361	0.0566
$\delta_{*,3}$	0.0600	0.0010	0	0.1749
$\delta_{*,4}$	0.0274	0.0722	0.0749	0

Furthermore, the above results implies that the most effective performance could be achieved even for simple topologies of the information layer. With the speed information, type IV (or III) could save a lot of communication cost in comparison with type IV (or V). With the angle information, type II (or III) could save a lot of communication cost in comparison with type IV, V, and VI.

5 Conclusions

This paper proposed a multi-layer multi-agent model, along with a performance index, to evaluate the damping controllers for the power system low frequency oscillation, from the viewpoint of the information-layer topology. The considered power system was described by a multi-agent model consisting of the control layer, the transmission network layer, and the information layer. The simulation results confirmed that the inter-area information flows have great impact on the inter-area low-frequency oscillation, while the information flows inside an area have less impact. However, how to model mathematically the impact of information-layer topology on the system performance and how to construct the information-flow structure for optimal indexes are still to be explored.

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