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A networked hierarchical control scheme for wide-area systems: A power system application

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Abstract

This paper presents a new networked hierarchical predictive sliding mode controller for the design of stabilizing signals to damp low frequency oscillations observed in geographically distributed networked power systems subject to communication network constraints. Firstly, through the generic framework of networked systems, a networked model is used for a distributed networked system in which network delays and data packet loss are considered in a wide area measurement system (WAMS). Then a hierarchical predictive sliding mode controller with robust reaching law is proposed to compensate the influence of WAMS communication latency and damp the inter-area oscillations. For this, firstly, the overall system is decomposed into small subsystems with non-sparse matrices and lower order; then a new suitable predictive sliding mode controller is designed to provide optimal performance. Furthermore, in order to coordinate the entire system, the gradient of interaction errors is used. The effectiveness of the proposed control framework is illustrated through numerical simulations on a 5-area, 16-machine power system with several interconnected areas. Simulation results show the capability of the proposed approach to enhance the networked power systems' damping in comparison with a conventional networked control method.

KEYWORDS

hierarchical control, networked control, power system stability, predictive sliding mode, wide area system

1 | INTRODUCTION

Distributed wide-area systems commonly appear in the real world, in the form of, for example, power grids, chemical plants, water distribution networks, traffic systems, etc. Systems are wide-area systems if they can be decoupled or decomposed into a number of interconnected/interacting subsystems or if their dimensions are so large that using the usual analysis, optimization, and control methods cannot achieve an acceptable answer during reasonable computational time and efforts [1]. Such typical motivating problems arise in the control of widely distributed multi-area power systems with severe interactions. These problems are mainly due to large dimensions, modeling errors, disturbances, and uncertainties in such systems.

The stability of modern power grids is one of the most important issues in the operation of these systems. The increasing size of wide-area electric power grids and the interconnection of these systems via weak tie-lines and heavy loading restrict the power transfer capability and challenge the operational system's security and economics [2]. The low frequency oscillatory dynamics can be damped through power system stabilizers (PSSs) and flexible AC transmission systems (FACTS) devices in which the control strategies are based on centralized or decentralized control frameworks. In the centralized control plans, whole measurements are computed and transmitted to a central controller for appraising, and then the obtained control commands are sent back to the power system. The centralized control scheme is known to provide the best performance (because it imposes the least constraints on the control signals), but the computational burden and organizational complexity related to the centralized controllers often makes their implementation impractical, especially for wide area power systems with highly interconnected subsystems and complex dynamics. Furthermore, the consequences of failures in a centralized control scheme can influence the overall system [3].

These issues have motivated considerable works on decentralized damping controllers. In these frameworks, the plant is decomposed into several subsystems with interconnections and several local controllers are installed on some subsystems in which no signal is transferred between local controllers. The decentralized damping controller-based methods reduce the complexity of designing and implementing power system damping controllers and also provide flexibility in dealing with local damping controller failures. In recent years, various decentralized controllers have been proposed for distributed multi-machine power systems [4,5]. Among these, hierarchical control as one of the proper solutions for wide-area systems provides an appropriate structure which reduces the computations through decomposition, coordination, and parallel processing [4]. One of the main properties of hierarchical control in comparison with centralized control is less complexity and computation, since the required memory for each subsystem is much less than the overall system [5].

On the other hand, with the increasing size and complexity of modern power systems, the damping control of spatially distributed power systems with traditional dedicated point-to-point wired links has become impractical. Recently, the advancements of WAMS in parallel with networked communication technologies have made the prospect of damping oscillation and enhancing the performance of geographically distributed power systems through remote signals a realistic one [6,7]. However, employing remote signals through the communication channels brings unavoidably serious difficulties, such as inevitable time-varying delays and data packet loss, into the design of networked control systems which will inevitably deteriorate the control performance or may even cause entire system instability [8,9].

In recent years, considerable research has been carried out using wireless communication networks to design wide-area damping controllers for distributed networked power systems. But, in most of the existing literature the effects of the communication network have been ignored and it is assumed that the measured signals transfer through an ideal communication network with no delays or packet dropouts. A few exceptions to this are [10–18].

In [10], the authors investigate the influence of network-induced delay to wide area power system stabilization, and the results show that the delay in feedback communication channels reduces control performance. In [11] the authors try to address the communication network-induced limitations by investigating the effects of packet dropouts on the oscillatory stability response of a networked controlled power system. In [12], a centralized controller based on linear matrix inequality is proposed for a closed-loop power system. However, only delay compensators can be obtained using this approach. In [13], time-delay compensation methods are developed to compensate for input delay in wide area power systems. In [14], a stabilizing controller is provided for the power system's multiple time delays. In [15] the authors propose a networked linear–quadratic regulator (LQR) control scheme for a dual-machine power system by considering communication-induced delays. In [16], a centralized networked wide area damping control scheme is introduced to provide supplementary signals for FACTS devices to damp inter-area oscillations. In [17] the authors use an adaptive phasor power oscillation damping controller to compensate the continuous time-varying delays in remote feedback signal. A fuzzy logic-based networked damping controller is proposed in [18].

Often the above stabilizing controllers are based on centralized control frameworks which face problems associated with centralized control. As a result, decentralized control is essential for flexible energy management to provide appropriate structure to reduce the computations through coordination and parallel processing.

This paper presents a new networked hierarchical predictive sliding mode controller (NHPSMC) scheme to design the stabilizing signals to damp the low frequency oscillations of wide-area networked interconnected power systems. In the suggested approach, firstly, a two-level hierarchical control strategy based on the interaction prediction principal (IPP) is used. Then, taking into account the predicted interaction, the performance of every subsystem is optimized by a new networked predictive sliding mode controller. In order to verify the efficiency and effectiveness of the proposed approach a wide-area networked power system with interconnected areas is considered. The effectiveness of the designed damping controller is illustrated by considering various operating conditions.

The remainder of the paper is organized as follows. The next section gives a brief summary of the IPP. A detailed description of the proposed NHPSMC design procedure is given in Section 3. The study power system and simulation results are presented in Section 4. Finally, some conclusions are drawn in Section 5.

2 | MODEL COORDINATION AND INTERACTION PREDICTION PRINCIPLE

In the hierarchical control of wide-area systems, the wide-area system is decomposed into smaller subsystems and each subsystem solves its own problem. Then a coordinator is used to coordinate the subsystems so that the optimal control solution is achieved for the overall system. It is assumed that the coupled subsystems influence—that is, interact with—each other. In order to eliminate and/or reduce the impact of the interactions, all of the subsystems should be coordinated, which is accomplished based on two principles: the interaction prediction principle (IPP) and the interaction balance principle (IBP). The IPP-based coordination approaches require less computing time and each subsystem can be transformed to an optimization problem. Thus, the formulation of centralized approaches can be employed to solve the problem. Consequently, the IPP-based coordination method is employed in this paper and described as follows [1].

For a wide area system, the system Pand cost function G are described as follows:

$$\begin{aligned} &P: U \times X \rightarrow Y \\ &G: U \times Y \rightarrow V \\ &G\left(\widehat{U}, P\left(\widehat{U}\right)\right) = \min G(U, P(U)) \end{aligned} \tag{1}$$

where U, X, Y, and V are system input, state variables, system output, and global cost function, respectively. The system is decomposed into m msubsystems and each subsystem is presented below:

$$\begin{aligned} &U = U_1 \times \cdots \times U_m \\ &X = X_1 \times \cdots \times X_m \\ &Y = Y_1 \times \cdots \times Y_m \\ &Z = Z_1 \times \cdots \times Z_m \\ &P_i = U_i \times Z_i \times X_i \rightarrow Y_i \end{aligned} \tag{2}$$

where Z_i Zi shows the interaction of the i^{th} subsystem with other subsystems. The following mapping gives the interface input appearing at the i^{th} subsystem, in the coupled system:

$$H_i: U \times X \rightarrow Z_i \ for \ \ i = 1, \cdots, m \tag{3}$$

In addition, the local performance function is presented as follows:

$$\begin{aligned} &g(U) = G(U, P(U)) = \sum_{i=1}^{m} g_i(U_i, Z_i) \\ &g_i(U_i, Z_i) = G(U_i, \ Z_i, \ P_i(U_i, Z_i) \ \ for \ i = 1, \cdots, m \end{aligned} \tag{4}$$

Suppose z_{pi} are the predicated interactions for the i^{th} subsystem which are calculated through the coordinator. Therefore, the subsystems can be shown as follows:

$$P_{iz_p} = P_i\left(u_i, z_{pi}\right) \ \ for \ i = 1, \cdots, m \tag{5}$$

The optimal control problem is to find $\widehat{u}_i$ to meet the following equation:

$$g_i\left(\widehat{u}_i, z_{pi}\right) = \min_{u_i \in U_i} g_i\left(u_i, z_{pi}\right), \qquad i = 1, \cdots, m \tag{6}$$

By applying the $\widehat{\mathrm{u}}_{\mathrm{i}}$ on subsystem equation, the real interaction is computed. The IPP expresses that the global optimum is obtained when the condition presented in (7), is satisfied:

$$z_{pi} = z_i \ for \ i = 1, \ldots, m \tag{7}$$

3 | THE PROPOSED NETWORKED HIERARCHICAL CONTROL SCHEME

Distributed networked wide-area systems consist of many coupled subsystems which exchange information through a communication network. However, due to finite bandwidth and possible data concussions in communication networks, transmission time delays and data packet dropouts are unavoidable in such distributed networked systems. Thus, to consider the effects of the above-mentioned network-induced problems in the controller design, a new model based on earlier work [19] is used for networked distributed wide-area systems.

In order to construct the DNWAS model featuring communication network imperfections containing induced time delay and data packet loss, assume that, at each k time step ($k = 0,1,\ldots,\infty$), the controller of the j^{th} sub-system transfers the state information of its relating sub-system, that is, $x_j(k)$, with a sampling time of T_s to the i^{th} sub-system, and the destination sub-system receives information packet at $k_r(r = 0,1,\ldots)$ instants. As the data packet disordering is a common phenomenon in communication networks, to avoid the wrong arrival data packet sequence, every data packet is labeled with a “time stamp” that includes the data of the relating sampling time. In addition, one buffer is embedded in each local controller. Each buffer holds the latterly arrived information packet until the achievement of the next one; once the newer data packet is received, its time stamp is reconciled with the time stamp of the current information packet. If the newly arrived data packet in the buffer is newer than the present data packet, then the buffer contents will be updated. If not, the latterly arrived data packet will be discarded. By using this strategy, a formal assurance is obtained that the control signal commands are constructed via the most recently available information packets.

In order to ensure that the time stamped data are precise, the sensors' clocks and the clocks of the whole subsystems' controller must be matched. Hitherto, several real-time clocks and well-established synchronization approaches are accomplished for this aim (for instance [20]).

Assume at instance k_r, the i^{th} sub-system receives a newer data packet containing the states data of the j^{th} sub-system, with a delay of $\tau_{ij}^{k_r}$. As a result, the i^{th} buffer relating to the i^{th} sub-system updates. Suppose now that the newer data packet arrives at instance $k = k_{r+1}$, and during the time k_r to k_{r+1} the data packet dropout phenomenon occurs consecutively in the telecommunication network channels for δ_k times. Hence, during the time k_r to k_{r+1}, the i^{th} local controller uses the data stored in its buffer which has been achieved at instance k_r which is indicated with $x_j^i(k)$. Therefore, the DNWAS model featuring communication channel imperfections inducing time delay and packet loss can be expressed as follows:

$$\begin{cases} k = k_r & : \ x_j^i(k) = x_j\left(k - \tau_{ij}^{k_r}\right) \\ k = k_r + 1 & : \ x_j^i(k) = x_j\left(k - \tau_{ij}^{k_r} - 1\right) \\ \quad \vdots & \\ k = k_r + \delta_k & : \ x_j^i(k) = x_j\left(k - \tau_{ij}^{k_r} - \delta_k\right) \\ k = k_{r+1} & : \ x_j^i(k) = x_j\left(k - \tau_{ij}^{k_{r+1}}\right) \end{cases}$$

Accordingly, the DNWAS model featuring random delays $\tau_{ij}^{k_r}$ and δ_k sequentially dropped information packets is represented via $x_j^i(k) = x_j\left(k - \tau_{ij}(k)\right)$, where $\tau_{ij}(k) = \tau_{ij}^{kr} + \delta_k$ denotes uncertain time-varying interconnection delay and implies a non-ideal characteristic of communication channels inclusive of random time delay and packet dropout. This interconnection delay satisfies $0 \le \tau_{ij}(k) \le \tau_{ijM}$ which τ_{ijM} is the maximum size of the delay.

Therefore, the complete model of the networked distributed wide-area system with communication network delays and uncertainties can be presented as follows:

$$\begin{cases} x(k+1) = (G + \Delta G)x(k) + (H + \Delta H)u(k) + (G_d + \Delta G_d)x(k - \tau(k)) \\ x(0) = x_0 \end{cases} \tag{8}$$

with the initial condition $x_i(0) = \phi_i(0)$. Also, x_i presents the state vector and u shows the control input. Moreover, G, G_d, and H are constant and real matrices. In addition, G and H indicate the system' s matrices and G_d shows the state delayed matrix. Also, ΔG, ΔG_d, and ΔH are system and input uncertainty matrices, respectively. Furthermore, $\tau(k)$ stands for uncertain random state delay and satisfies $0 \le \tau(k) \le \tau_M$ which τ_M is the maximum size of the delay.

> *Remark* 1. According to [21,22], if the characteristics of the communication network are recognized, then the maximum size of delay (upper bound of delay) can be approximated. Thus, in this work, it is assumed that the considered upper bound of time delay is a known and fixed integer.

In the proposed method, the considered networked controller is treated as a two-level hierarchical controller where each local controller performs local actions in the first level and coordinates the overall system in the second level to achieve the optimal control solutions. These two level procedures are explained below.

3.1 | The first level

Consider a discrete-time uncertain networked distributed wide-area system described as (8). The optimal control problem is then to find inputs $u(0),\cdots,u(N-1)$ by minimizing the following quadratic performance index:

$$J = \frac{1}{2}x^T(N)Sx(N) + \frac{1}{2}\sum_{k=0}^{N-1}\left[x^T(k)Qx(k) + u^T(k)Ru(k)\right] \tag{9}$$

The decomposition of the networked distributed wide-area system (8) into m subsystems is represented as follows:

$$\begin{cases} x_i(k+1) = (G_{ii} + \Delta G_{ii})x_i(k). + (H_{ii} + \Delta H_{ii})u_i(k) \\ \qquad + (G_{di} + \Delta G_{di})x_i(k - \tau(k)) + z_i(k) + \Delta z_i(k) \\ x_i(0) = x_{i_0}, \quad i = 1,\ 2,\ \cdots,\ m \end{cases} \tag{10}$$

where G_{ii} and $G_{di} \in R^{nm_i \times nm_i}$, $H_{ii} \in R^{nm_i}$ and $H_{di} \in R^{nm_i}$. The interaction of other subsystems with the i^{th} subsystem is also defined by z_i as follows:

$$\begin{cases} z_i = \sum_{\substack{j=1 \\ j \neq i}}^{m} G_{ij}x_j(k) + H_{ij}u_j(k) \\ \Delta z_i = \sum_{\substack{j=1 \\ j \neq i}}^{m} \Delta G_{ij}x_j(k) + \Delta H_{ij}u_j(k) \end{cases} \tag{11}$$

The term $(G_{di}+\Delta G_{di})x_i(k-\tau(k))$can be considered as a disturbance term [23]. Thus (10) can be rewritten (10) as follows:

$$\begin{cases} x_i(k+1) = (G_{ii}+\Delta G_{ii})x_i(k) + (H_{ii}+\Delta H_{ii})u_i(k) + \\ \qquad z_i(k) + \Delta z_i(k) + v(k) \\ x_i(0) = x_{i_0}, \quad i = 1, 2, \cdots, nm_i \\ v(k) = (G_{di}+\Delta G_{di})x_i(k-\tau(k)) \end{cases} \tag{12}$$

Moreover, the local cost function for each subsystem is described as follows:

$$J_i = \frac{1}{2}x_i^T(N)S_ix_i(N) + \frac{1}{2}\sum_{k=0}^{N-1}\left[x_i^T(k)Q_ix_i(k) + u_i^T(k)R_iu_i(k)\right] \\ i = 1, \cdots, m \tag{13}$$

The optimal control values for the i^{th} subsystem, given in (10), are calculated considering the cost functions presented in (13). The Lagrange coefficient-based approach can be used to obtain the optimal control signals.

Therefore, the new cost function L_i using a set of Lagrange coefficients $\lambda_i(1),\cdots,\lambda_i(N)$ is defined as follows:

$$\begin{aligned} L_i = {} & \frac{1}{2}x_i^T(N)S_ix(N) + \frac{1}{2}\sum_{k=0}^{N-1}\left[x_i^T(k)Q_ix(k) + u_i^T(k)R_iu(k)\right] \\ & + \lambda_i^T(k+1)[(G_{ii}+\Delta G_{ii})x_i(k) + (H_{ii}+\Delta H_{ii})u_i(k) \\ & + z_{pi}(k) + v(k) - x_i(k+1)] \\ & + [(G_{ii}+\Delta G_{ii})x_i(k) + (H_{ii}+\Delta H_{ii})u_i(k) + z_{pi}(k) \\ & + v(k) - x_i(k+1)]^T\lambda_i^T(k+1) \qquad i = 1, \ldots, m \end{aligned} \tag{14}$$

where z_{pi} is the predicted interaction where predicted by the coordinator. To minimize L_i, the essential conditions for optimality are as follows:

$$\frac{\partial L_i}{\partial x_i^T(k)} = Q_ix_i(k) + (G_{ii}+\Delta G_{ii})^T\lambda_i(k+1) - \lambda_i(k) = 0 \\ k = 1, \cdots, N-1 \tag{15}$$

$$\frac{\partial L_i}{\partial x_i(N)} = S_ix_i(N) + \lambda_i(N) = 0 \tag{16}$$

$$\frac{\partial L_i}{\partial u_i^T(k)} = R_iu_i(k) + (H_{ii}+\Delta H_{ii})^T\lambda_i(k+1) = 0 \\ k = 0, \cdots, N-1 \tag{17}$$

$$\frac{\partial L_i}{\partial \lambda_i(N)} = (G_{ii}+\Delta G_{ii})x_i(k-1) + (H_{ii}+\Delta H_{ii})_i(k-1) \\ +z_{pi}(k-1) + v(k-1) - x_i(k) = 0, \quad k = 1, \cdots, N \tag{18}$$

(17) can be rewritten as (19):

$$u_i(k) = -R_i^{-1}(H_{ii}+\Delta H_{ii})^T\lambda_i(k+1) = 0 \quad k \\ = 1, \cdots, N-1 \tag{19}$$

By substituting (19) in (10), the state space model of the i^{th} subsystem is given as follows:

$$x_i(k+1) = (G_{ii}+\Delta G_{ii})x_i(k) - (H_{ii}+\Delta H_{ii})R_i^{-1}(H_{ii}+\Delta H_{ii})^T \\ + \lambda_i(k+1) + z_{pi}(k) + v(k) \\ x_i(0) = x_{i0}, \quad k = 0, \ldots, N-1. \tag{20}$$

Consider (21) and (22) are met.

$$\det\left[(H_{ii}+\Delta H_{ii})^T(H_{ii}+\Delta H_{ii})\right] \neq 0 \tag{21}$$

$$(H_{ii}+\Delta H_{ii})\left((H_{ii}+\Delta H_{ii})^T(H_{ii}+\Delta H_{ii})\right)^{-1}(H_{ii}+\Delta H_{ii})^T = I \tag{22}$$

Thus, $z_{pi}'(k)$ can be presented in the form of (23):

$$z_{pi}'(k) = \left((H_{ii}+\Delta H_{ii})^T((H_{ii}+\Delta H_{ii})\right)^{-1}(H_{ii}+\Delta H_{ii})^Tz_{pi}(k) \\ z_{pi}(k) = (H_{ii}+\Delta H_{ii})z_{pi}'(k) \tag{23}$$

Afterward, by using (23), (20) can be rewritten as follows:

$$x_i(k+1) = (G_{ii}+\Delta G_{ii})x_i(k) + (H_{ii}+\Delta H_{ii})\left(u_i(k) + z_{pi}'(k)\right) + v(k) \\ = (G_{ii}+\Delta G_{ii})x_i(k) + (H_{ii}+\Delta H_{ii})u_i'(k) + v(k) \tag{24}$$

By substituting (23) in (24), the optimal control solution of ith subsystem is obtained as follows:

$$u_i(k) = u_i'(k) - \left((H_{ii}+\Delta H_{ii})^T(H_{ii}+\Delta H_{ii})\right)^{-1}(H_{ii}+\Delta H_{ii})^Tz_{pi}(k) \tag{25}$$

Afterward, by decomposing the overall wide area system to m small-scale system, the $u_i'(k)$ can be computed by using the predictive sliding mode controller. In the following, a new hybrid local control strategy is proposed for the suggested hierarchical controller scheme which combines the advantages of the SMC and MPC methods, to achieve better performance and overcome most of their difficulties. The main idea of the presented approach is to define the prediction of the sliding surface into the control cost function.

System (24) can be rewritten in the following form:

$$x(k+1) = G_{ii}x_i(k) + G_{di}x_i(k-\tau(k)) + H_{ii}u_i^{'}(k) + W_i(k) \tag{26}$$

where.

$$W_i(k) = \Delta G_{ii}x_i(k) + \Delta H_{ii}u_i^{'}(k) + \Delta G_{di}x_i(k-\tau(k)) \tag{27}$$

The sliding mode function is defined as.

$$S_i(k) = C_{ii}x_i(k) \tag{28}$$

where $C_{ii} \in R^{1\times nm_i}$ is the coefficients vector which is computed using the LMI approach in [24], so that the sliding function is stable.

> *Remark.* The considered sliding mode function is simple, handles the reaching process directly, and facilitates the calculating of control law [25], and its efficiency is supported in many works [25–27], as well as in the current paper. However, chattering in the steady state is the main difficulty for some plants, owing to the discontinuous switching control exerted on the plant, which excites the un-modeled high frequency dynamics of the system [26]. There are various works that try to improve this sliding function [26,27].

For system (24) the condition to achieve the sliding surface is introduced below:

$$|S_i(k+1)| - |S_i(k)| < 0 \tag{29}$$

Then, the sliding mode function (29) will be defined as:

$$\begin{aligned} s_i(k+1) &= C_{ii}x_i(k+1) \\ &= C_{ii}\left[G_{ii}x_i(k) + G_{di}x_i(k-\tau(k)) + H_{ii}u_i^{'}(k) + W_i(k)\right] \\ &= C_{ii}\left[G_{ii}x_i(k) + G_{di}x_i(k-\tau(k)) + H_{ii}u_i^{'}(k)\right] + C_{ii}W_i(k) \end{aligned} \tag{30}$$

To obtain some desired performances, such as strong robustness, fast convergence, and chattering elimination, we introduce a modified reaching law, based on [25], to ensure convergence of the sliding function $S_i(k)$ to zero. To ensure a quasi-sliding mode, the sliding mode function must verify the following reaching law:

$$s_i(k+1) = s_i(k) - m\,\mathrm{sgn}(s_i(k)) \tag{31}$$

where m is the q > 0 discontinuous term magnitude.

Now by employing (30) and applying the sliding mode control scheme for the system described in (26) and considering the reaching law (31) as a reference sliding mode trajectory, the following equations are obtained:

$$\begin{cases} s_{ri}(k+p) = s_{ri}(k+p-1) - m\,\mathrm{sgn}(s_{ri}(k+p-1)) \\ s_{ri}(k) = s_i(k) \end{cases} \tag{32}$$

If there are no disturbances, the sliding function (28) value at time $(k+p)$ is.

$$\begin{aligned} s_i(k+p) = {} & C_{ii}G_{ii}^{p}x_i(k) + \sum_{j=1}^{p} C_{ii}G_{ii}^{j-1}H_{ii}u_i^{'}(k+p-j) \\ & + \sum_{s=1}^{p} C_{ii}G_{ii}^{s-1}G_{di}x_i(k-\tau(k)+p-s) \end{aligned} \tag{33}$$

where $k \in Z$ and $p \in$ Z. The aim is to design a predictive sliding mode controller. Thus, by using MPC as a predictor, the value of the sliding mode in sample k on $(k - p)$ can be computed as follows:

$$\begin{aligned} s_i(k|k-p) = {} & C_{ii}G_{ii}^{p}x_i(k-p) + \sum_{j=1}^{p} C_{ii}G_{ii}^{j-1}H_{ii}u_i^{'}(k-j) \\ & + \sum_{s=1}^{p} C_{ii}G_{ii}^{s-1}G_{di}x_i(k-\tau(k)-s) \end{aligned} \tag{34}$$

Equation (34) can be presented in the vector form as.

$$S_{pi}(k+1) = \Gamma_i x_i(k) + \Omega_i U_i^{'}(k) + ZX_{di}(k) \tag{35}$$

where.

$$\begin{aligned} S_{pi}(k+1) &= [s_i(k+1), s_i(k+2), ..., s_i(k+N_2)]^T \\ S_{pi}(k) &= [s_i(k), s_i(k+1), ..., s_i(k+N_2-1)]^T \end{aligned} \tag{36}$$

$$X_{di}(k) = [x_i(k-\tau(k)), x_i(k-\tau(k)+1), ..., x_i(k-\tau(k)+N_2-1)]^T \tag{37}$$

$$U_i^{'}(k) = \left[u_i^{'}(k), u_i^{'}(k+1), ..., u_i^{'}(k+M-1)\right]^T \tag{38}$$

$$\Gamma_i = \left[(C_{ii}G_{ii})^T \;\; (C_{ii}G_{ii}^2)^T \;\; ...., \left(C_{ii}G_{ii}^{N_2}\right)^T\right]^T \tag{39}$$

$$\Omega_i = \begin{bmatrix} C_{ii}H_{ii} & 0 & \cdots & \cdots & 0 \\ C_{ii}G_{ii}H_{ii} & C_{ii}H_{ii} & \cdots & \cdots & 0 \\ \vdots & \vdots & \cdots & \cdots & \vdots \\ C_{ii}G_{ii}^{M-1}H_{ii} & C_{ii}G_{ii}^{M-2}H_{ii} & \cdots & C_{ii}G_{ii}H_{ii} & CH_{ii} \\ \vdots & \vdots & \cdots & \cdots & \vdots \\ C_{ii}G_{ii}^{N_2-2}H_{ii} & C_{ii}G_{ii}^{N_2-3}H_{ii} & \cdots & C_{ii}G_{ii}^{N_2-M}H_{ii} & C_{ii}G_{ii}^{N_2-M-1}H_{ii} \\ C_{ii}G_{ii}^{N_2-1}H_{ii} & C_{ii}G_{ii}^{N_2-2}H_{ii} & \cdots & C_{ii}G_{ii}^{N_2-M+1}H_{ii} & C_{ii}G_{ii}^{N_2-M}H_{ii} \end{bmatrix} \tag{40}$$

$$Z = \begin{bmatrix} C_{ii}G_{di} & 0 & \cdots & \ldots & 0 \\ C_{ii}G_{ii}G_{di} & C_{ii}G_{di} & \cdots & \ldots & 0 \\ \vdots & \vdots & \cdots & \cdots & . \\ . & . & \cdots & . & . \\ \vdots & \vdots & \cdots & \cdots & \vdots \\ . & . & \cdots & . & . \\ C_{ii}G_{ii}^{N-1}G_{di} & C_{ii}G_{ii}^{N-2}G_{di} & \cdots & C_{ii}G_{ii}^{N-N+1}G_{di} & C_{ii}G_{di} \end{bmatrix} \tag{41}$$

where N_2 and $M$are the prediction horizon and control horizon, respectively. Also, the minimum costing horizon N_1 is chosen equal to one.

In practice, to correct the future predictive sliding mode value $s_i(k+p)$ we introduce the error between the practical sliding mode value $s_i(k)$ and the predictive sliding mode value $s_i(k|\,k-p)$. Therefore, the output of the sliding mode prediction $\widetilde{s}_{pi}(k+p)$ is given as follows:

$$\begin{aligned} \widetilde{s}_{pi}(k+p) &= s_i(k+p) + h_p e_i(k) \\ &= C_{ii}G_{ii}^{p}x_i(k) \\ &\quad +\sum_{j=1}^{p} C_{ii}G_{ii}^{j-1}H_{ii}u_i^{'}(k+p-j) \\ &\quad +\sum_{s=1}^{p} C_{ii}G_{ii}^{s-1}G_{di}x_i(k-\tau(k)+p-s) \\ &\quad +h_p e_i(k) \end{aligned} \tag{42}$$

where $e_i(k) = s_i(k) - s_i(k|\,k-p)$, $h_p = \operatorname{diag}\left[h_p^1, h_p^2, .., , h_p^m\right]$ and $h_p^j > 0$ is a correction factor. (42) can be rewritten in the following form:

$$\widetilde{S}_{pi}(k+1) = S_{pi}(k+1) + H_{pi}E_i(k) \tag{43}$$

where.

$$\widetilde{S}_{pi}(k+1) = \left[\widetilde{s}_{pi}(k+1), \widetilde{s}_{pi}(k+2), \ldots, \widetilde{s}_{pi}(k+N_2)\right]^T \tag{44}$$

$$H_p = \operatorname{diag}[h_1,\, h_2,\, \ldots,\, h_{N_2}] \tag{45}$$

$$E_i(k) = S_i(k) - S_{mpi}(k) \tag{46}$$

$$S_i(k) = [s_i(k), s_i(k), \ldots, s_i(k)]_{1\times N_2} \tag{47}$$

$$S_{mpi}(k) = [s_i(k|k-1), s_i(k|k-2), \ldots, s_i(k|k-N_2)]^T \tag{48}$$

Then the cost function regarding the MPC sliding mode controller is defined as.

$$\begin{aligned} j_{pi} &= \sum_{j=1}^{N_2} q_j\left[\widetilde{s}_{pi}(k+j) - s_{ri}(k+j)\right]^2 \\ &\quad + \sum_{l=1}^{M} g_l\left[u_i^{'}(k+l-1)\right]^2 \end{aligned} \tag{49}$$

where $s_{ri}(k+j)$ is the sliding mode reference trajectory, and q_j and g_l are the weight coefficients. In order to simplify the synthesis of the controller, we consider $q_j = 1$ and $g_l = g$. Thus, the following corresponding optimization cost function is written by.

$$\begin{aligned} J_{pi} &= \sum_{j=1}^{N_2} \left[\widetilde{s}_{pi}(k+j) - s_{ri}(k+j)\right]^2 \\ &\quad + \sum_{l=1}^{M} g\left[u_i^{'}(k+l-1)\right]^2 \end{aligned} \tag{50}$$

(50) can be written in a vector form as.

$$\begin{aligned} j_{pi} &= \left\|\widetilde{S}_{pi}(k+1) - S_{ri}(k+1)\right\| + \left\|U_i^{'}(k)\right\|_G^2 \\ &= \left[\Gamma_i x_i(k) + \Omega_i U_i^{'}(k) + ZX_{di}(k) + H_p E_i(k) - S_{ri}(k+1)\right]^T \\ &\quad \left[\Gamma_i x_i(k) + \Omega_i U_i^{'}(k) + ZX_{di}(k) + H_p E_i(k) - S_{ri}(k+1)\right] + U_i^{'}(k)^T G_i U_i^{'}(k) \end{aligned} \tag{51}$$

where.

$$\begin{aligned} S_{ri}(k+1) &= [s_{ri}(k+1), s_{ri}(k+2), \ldots, s_{ri}(k+N_2)]^T \\ X_{di}(k) &= [x_i(k-\tau(k)), x_i(k-\tau(k)+1), \ldots, x_i(k-\tau(k)+N_2-1)]^T. \end{aligned} \tag{52}$$

Eventually with $\dfrac{\partial j_{pi}}{\partial U^{'}(k)} = 0$ the optimal control law can be obtained as.

$$U_i^{'}(k) = -\left(\Omega_i{}^T\Omega_i + G\right)^{-1}\Omega_i{}^T\left[\Gamma_i x_i(k) + ZX_{di} + H_p E_i(k) - S_{ri}(k+1)\right] \tag{53}$$

Because of optimization, only the present control input signal is implemented; next time the control signal $u_i^{'}(k+1)$ will be calculated recursively by the control law. Now, the control command $u_i(k)$, state variables $x_i(k+1)$, and computed interactions $z_i(k)$ are obtained from (25), (20), and (11) respectively.

3.2 | The second level

Suppose the error vector as (54):

$$e_i(k) = z_i(k) - z_{pi}(k) \tag{54}$$

Then the vector of error will be.

$$e_{(m\times N)\times 1} = z - z_p \tag{55}$$

where.

$$z = \left[z_1^T \; z_2^T \; \ldots, z_m^T\right]^T \tag{56}$$

$$z_i = \left[z_i^T(0) \; z_i^T(1) \; \ldots, z_i^T(N-1)\right]^T \tag{57}$$

$$z_p = \left[z_{p11}^T \; z_{p2}^T \; \ldots, z_{pm}^T\right]^T \tag{58}$$

$$z_{pi} = \left[z_{pi}^T(0) \; z_{pi}^T(1) \; \ldots, z_{pi}^T(N-1)\right]^T \tag{59}$$

Then the cost function is presented as:

$$J_e = \frac{1}{2} e^T e \tag{60}$$

Moreover, the gradient of the error vector is calculated as follows:

$$\frac{\partial e}{\partial z_p} = \frac{\partial z}{\partial z_p} - I \tag{61}$$

Then, for $0 \le \eta \le 1$, $\Delta_{z_p}$is computed by employing (60) and (61) as follows:

$$\Delta_{z_p} = -\eta\left(\frac{\partial e^T}{\partial z_p} e\right) = -\eta \frac{\partial z^T}{\partial z_p} e + \eta (z - z_p) \tag{62}$$

Thus, the predicted interactions are updated via (63):

$$Z_p^{l+1} = (1-\eta) z_p^l + \eta Z^l - \eta \left(\frac{\partial z^l}{\partial z_p^l}\right)^T \left(z^l - z_p^l\right) \tag{63}$$

in which affects the convergence rate of the predicted interactions during the updating stage and l is the iteration index. In order to decrease computational complexity and increase the convergence rate, the term $\eta\left(\frac{\partial z^l}{\partial z_p^l}\right)^T \left(z^l - z_p^l\right)$ is ignored in (63).

4 | SIMULATION RESULTS

In this paper a 5-area, 16-machine power system, as indicated in Figure 1, is employed for simulation studies. A comprehensive description of the system containing network and dynamic data is presented in [28] which are employed to simulate in MATLAB/SIMULINK. Here, the proposed method in [29] is adopted to extract the model of the considered interconnected power system. Commonly, for a multi-area power system with N machines,

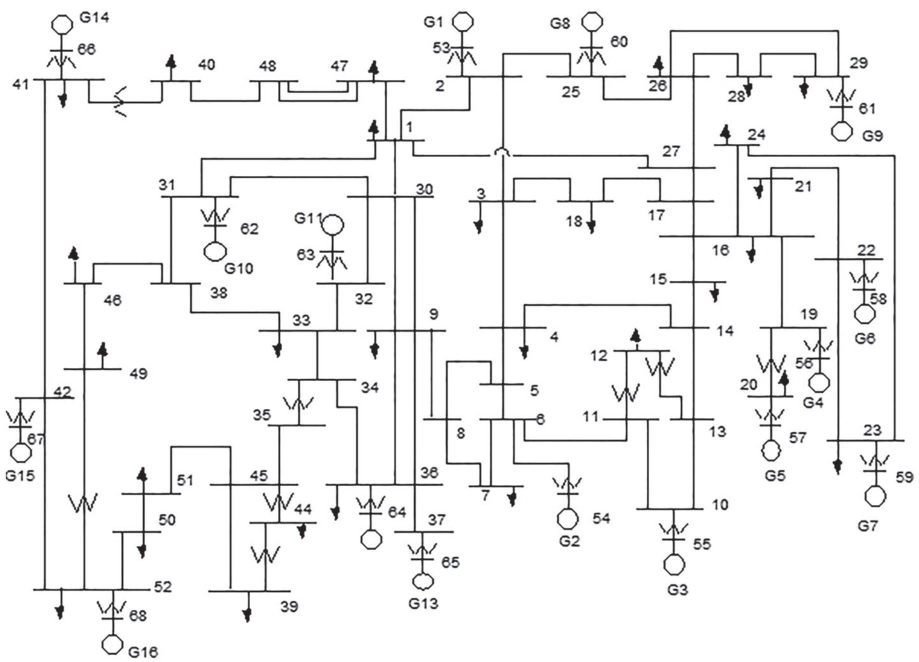

FIGURE 1 Single-line diagram of a 5-area, 16-machine power system

the model of the i^{th} sub-system ($i = 1,2,...,N$) can be described as follows. The nomenclatures of the systems' parameters are given in Table 1.

$$\dot{x}_i(t) = A_i x_i(t) + B_i u_i(t) + \sum_{j \in N_i,\, i \neq j} A_{ij} x_j(t) \quad i = 1,\, 2,\, ...,\, N \tag{64}$$

where.

$$x_i = \begin{bmatrix} x_{1i} \\ x_{2i} \\ x_{3i} \end{bmatrix} = \begin{bmatrix} \Delta\delta_i \\ \Delta\omega_i \\ \Delta E'_{qi} \end{bmatrix}$$

$$A_i = \begin{bmatrix} 0 & 1 & 0 \\ \dfrac{1}{J_i}\sum\limits_{\substack{j=1 \\ j \neq i}}^{n} E'_{qio}.E'_{qjo} GS_{ijo} & -\dfrac{D_i}{J_i} - \dfrac{2G_{ii}E'_{qio}}{J_i} - \dfrac{1}{J_i} & \sum\limits_{\substack{j=1 \\ j \neq i}}^{n} E'_{qjo}.BS_{ijo} \\ -\dfrac{(x_{di} - x'_{di})}{T'_{doi}} \sum\limits_{\substack{j=1 \\ j \neq i}}^{n} E'_{qjo}.BS_{ijo} & 0 & -\dfrac{1}{T'_{doi}} + \dfrac{(x_{di} - x'_{di})}{T'_{doi}} B_{ii} \end{bmatrix}$$

$$B_i = \begin{bmatrix} 0 \\ 0 \\ \dfrac{1}{T'_{doi}} \end{bmatrix} A_{ij} = \begin{bmatrix} 0 & 0 & 0 \\ \dfrac{1}{J_i} E'_{qio}.E'_{qjo}.GS_{ijo} & 0 & \dfrac{1}{J_i} E'_{qio}.BS_{ijo} \\ -\dfrac{(x_{di} - x'_{di})}{T'_{doi}} E'_{qjo}.BS_{ijo} & 0 & -\dfrac{(x_{di} - x'_{di})}{T'_{doi}}.GS_{ijo} \end{bmatrix}.$$

In (64) u_i is the input signal of the automatic voltage regulator (AVR) which must be applied to each machine. Moreover, N_i stands for the set of generators which are coupled with the i^{th} machine. Also, A_i and B_i are the matrices of the system and A_{ij} denotes the interconnection matrix. In addition we have, $GS_{ijo} = G_{ij}\sin(\delta_{ijo}) - B_{ij}\cos(\delta_{ijo})$ and $BS_{ijo} = B_{ij}\sin(\delta_{ijo}) - G_{ij}\cos(\delta_{ijo})$.

TABLE 1 Power grid parameters

Parameter/ variable	Description
J_i,D_i	Inertia of the rotor and damping factor
T'_{doi}	Direct-axis transient time constant
x_{di}	Direct axis reactance
x'_{di}	Direct-axis transient reactance
δ_i	Power angle of the i^{th} generator (rad)
ω_i	Relative speed of the i^{th} generator (rad)
E'_{qi}	Transient EMF in the quadrature axis
E_{qi}	EMF in the quadrature axis
G_{ij}+jB_{ij}	i^{th} row and j^{th} column element of nodal transient
	Admittance matrix after eliminating all physical
	Bus-bars

$\delta_{ij}(t) = \delta_i(t) - \delta_j(t)$

The non-ideal communication network is considered with random delays $\tau_i(k)$ which vary between 0 and 60 ms.

The highest possible value of the sampling time for such a power system is obtained at approximately 50 ms. As a result, a sampling time of 20 ms is chosen in this paper.

In order to show the ability and effectiveness of the proposed method, another networked wide-area damping controller, which is presented in [10], is applied for comparison. To investigate the effectiveness of the proposed

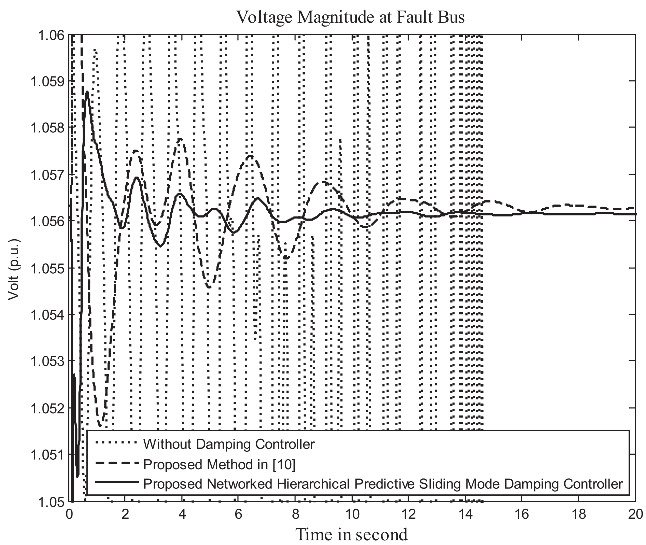

FIGURE 2 The voltage magnitude at the fault bus in case 1

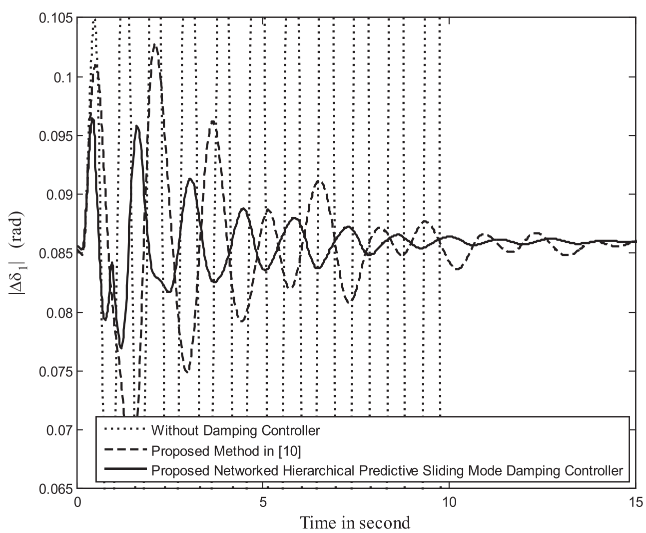

FIGURE 3 Generator 1 response to a line-to-ground fault when a non-ideal communication is considered (case 1)

hierarchical method compared to other methods, two various operating conditions are considered as follows.

Case 1. Considering a non-ideal communication network and applying a line-to-ground fault in one of the tie lines at bus 26 and persisting for 50 ms.

Case 2. Considering a non-ideal communication network and applying a three-phase fault in one of the tie lines at bus 26 and persisting for 50 *ms*.

In order to implement the proposed approach, the prediction horizon N_2 and the control horizon M are chosen as 5 and 3, respectively. The discrete step is equal to $\Delta t = 0.1$ *sec*. Also, two weighting matrices are set to one. Moreover, $G = 0.0001 * I_{M \times M}$.

Furthermore, for the sliding mode controller, we must satisfy $m > |W_i(k)|$ for all k. So, m is chosen as 0.20.

Figures 2–5 show the obtained results in Case 1; Figure 2 denotes the voltage magnitude at the fault bus. Furthermore, the generator G_{13} is selected as the reference machine and the generators' angles difference between G_{13} and generators G_1, G_3 and G_9 are calculated over the simulation time and provided in Figures 3–5. Figures 6–9 present the obtained results for Case 2. These figures verify the superiority of the proposed NHPSMC method in comparison to the proposed method in [10] despite the large fault and non-ideal communication network.

For better clarification of the enhancement of the system by the suggested approach, in comparison to the

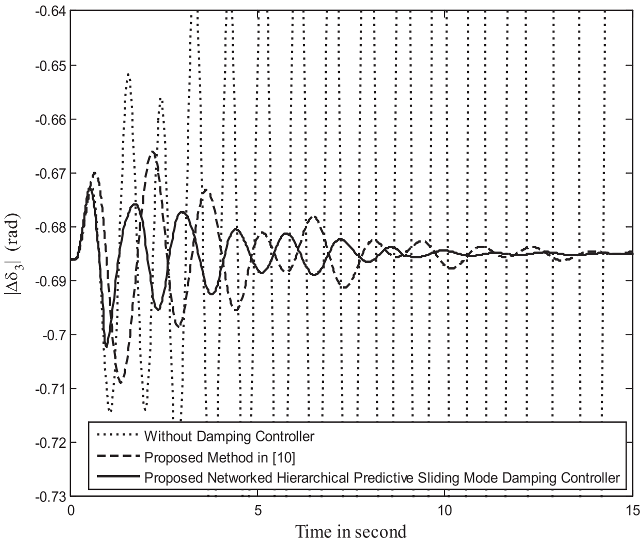

FIGURE 4 Generator 3 response to a line-to-ground fault when a non-ideal communication is considered (case 1)

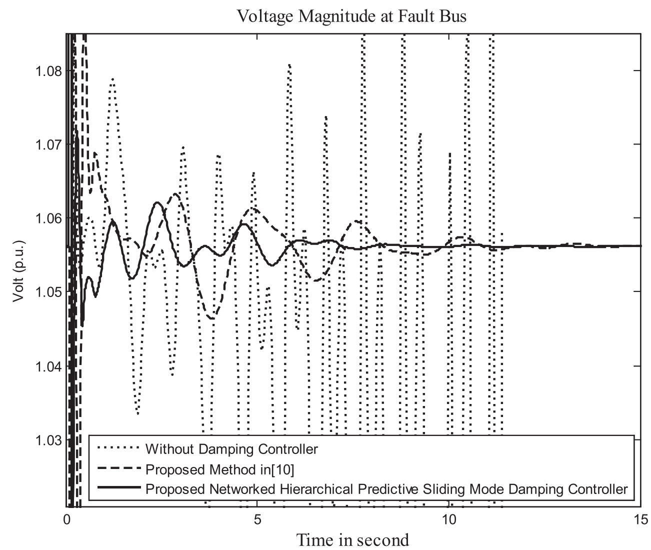

FIGURE 6 Voltage magnitude at the fault bus in case 2

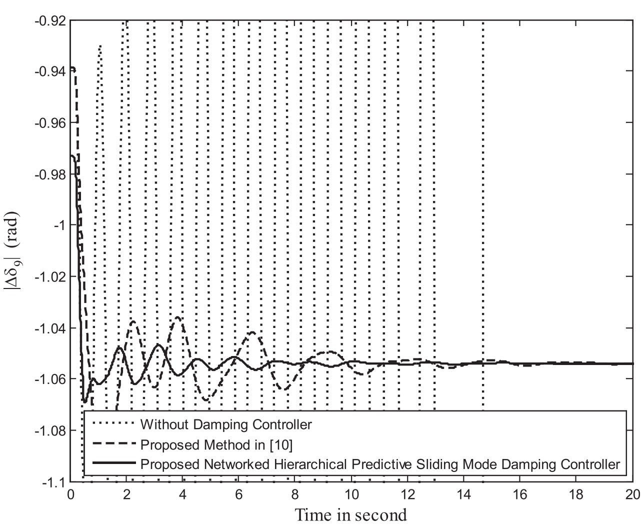

FIGURE 5 Generator 9 response to a line-to-ground fault when a non-ideal communication is considered (case 1)

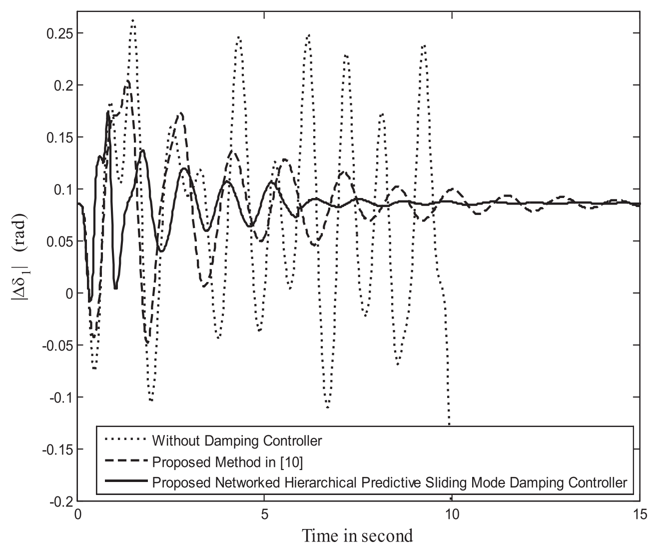

FIGURE 7 Generator 1 response to a three-phase fault when a non-ideal communication is considered (case 2)

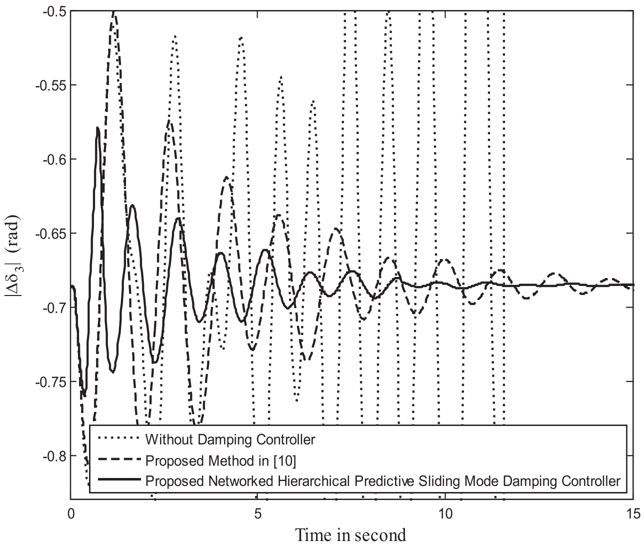

FIGURE 8 Generator 3 response to a three-phase fault when a non-ideal communication is considered (case 2)

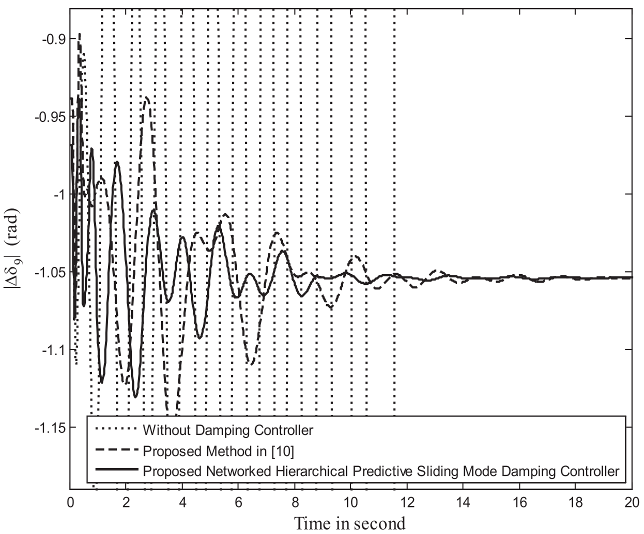

FIGURE 9 Generator 9 response to a three-phase fault when a non-ideal communication is considered (case 2)

method given in [10], two performance indices, PI_1 and PI_2, presented in (65) and (66), are computed for the obtained results:

$$PI_1 = \sum_{i=1}^{m} \int_{t=0}^{t=t_{sim}} (t\Delta\delta_i)^2 dt \tag{65}$$

$$PI_2 = \sum_{i=1}^{m} \int_{t=0}^{t=t_{sim}} (\Delta\delta_i)^2 dt \tag{66}$$

where m denotes the number of generators and t_{sim} stands for the simulation time. It should be mentioned that the lower value for the considered indices displays better system performance in terms of the overshoots and settling time. Table 2 reveals that the values PI_1 and

TABLE 2 Obtained values of performance indices

Method	Operating condition	PI_1	PI_2
Method in [10]	Applying a line-to-ground fault	1.751	1.727
	Applying a three-phase fault	1.895	1.849
NHPSMC	Applying a line-to-ground fault	1.674	1.610
	Applying a three-phase fault	1.591	1.555

PI_2 with the proposed NHPSMC approach are much smaller than the method given in [10].

5 | CONCLUSIONS

In this paper a new networked hierarchical two-level predictive sliding mode power system damping controller is proposed to damp network-distributed wide-area power system low frequency oscillations. It was constructed based on a two-level hierarchical structure and a networked predictive sliding mode local controller. Furthermore, the IPP based on the gradient of the interaction prediction errors related to the predicted interactions is used for coordination of the overall system. It is applied successfully to design stabilizing signals to damp the networked distributed wide-area power system low frequency oscillations. The effectiveness of the designed damping controller is illustrated by considering various operating conditions. The proposed approach is compared with a networked control-based method through time domain simulation. The comparisons show the superiority of the proposed damping controller in improving the stability of the system. The proposed method can be applied easily to higher-order systems and other large-scale processes.

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