Hindawi
Journal of Electrical and Computer Engineering
Volume 2019, Article ID 4261304, 14 pages
https://doi.org/10.1155/2019/4261304

Research Article

A Distributed AGC Method considering Two-Channel Random Delays and Their Difference between Interconnected Power Systems

Xilin Zhao [1], **Zhenyu Lin** [1], **Bo Fu** [1], **Yang Yang** [2], **and Jimin Ma** [1]

[1] *Hubei Key Laboratory for High-efficiency Utilization of Solar Energy and Operation Control of Energy Storage System, Hubei University of Technology, Wuhan 430068, China*
[2] *Times Electric CO. LTD, Zhuzhou China Railway Rolling Stock Corporation, Zhuzhou 412000, China*

Correspondence should be addressed to Xilin Zhao; zhaoxl@mail.hbut.edu.cn and Bo Fu; fubofanxx@mail.hbut.edu.cn

Received 26 November 2018; Revised 26 February 2019; Accepted 11 March 2019; Published 11 April 2019

Academic Editor: Renato Procopio

With the emergence of the concept of smart grid, the networked automatic generation control (AGC) method has been more and more important for secondary frequency control due to its characteristics such as openness and flexibility. However, the networked AGC system also presents some defects such as time delays and packet dropouts. The existence of time delays makes the traditional AGC strategies more challenging. A novel AGC method is proposed in this paper to mitigate the negative effects of time delays. Firstly, a multiarea power system model is built under the consideration of two-channel time delays: from controller to actuator and from sensor to controller. More practically, the difference of delays between areas is also exhibited in the model. Thus, from the predictive characteristics of model predictive control (MPC), a method of selection with optimization is presented to obtain the appropriate control variable when delays exist. Furthermore, three cases, (a) no processing for delay, (b) control sequence selection, (c) control sequence selection with optimization, are analyzed. The frequency and area control error (ACE) performance are evaluated with step load perturbation and random load perturbation. The simulation results indicate that the system controlled by the proposed method has desired dynamic performances. Consequently, the feasibility and effectiveness of the proposed method are verified.

1. Introduction

Automatic generation control (AGC) is an important research field in power system operation and control to supply reliable electric power with good quality. As a fundamental characteristic of electric power operations, frequency of the system deviates from its nominal value due to load and resource variation. The main role of the AGC is to resist the frequency deviations of the power system to maintain the system frequency close to its scheduled value [1–5].

Traditionally, a large power grid is usually composed of interconnected subpower systems to improve the system's reliability. In this case, each subpower system has its own AGC scheme in an energy management system. These schemes are responsible for maintaining a nominal frequency and stabilizing fluctuant tie-line flows to scheduled value. Therefore, a control strategy is required in each interconnected power system in order to not only maintain constancy of frequency but also achieve zero steady state error of desired tie-line flows and to minimize ACEs.

In the previous studies, proportional integral derivative (PID) controller is the most popular method applied to AGC. Conventional PID controller is designed with fixed structure and constant parameters. Due to the nonlinear characteristic of power system, conventional PID controllers may not have the desired control performance. Therefore, in order to improve system performance when considering parameter uncertainty and load disturbances, some techniques, such as fuzzy theory or optimization, were brought up to combine with conventional PID controller. Khooban et al. [6] and Sahu et al. [7] discussed different optimization methods to optimize the parameters of the PID controller to pursue better control performance. Xu et al. [8] proposed a dynamic gain-tuning control (DGTC) method for AGC with effects of wind resources. With the control method, the PI control parameters can be automatically and dynamically calculated according to different disturbances in a power system. Gheisarnejad and Khooban [9] presented a fuzzy PID controller for LFC in multi-microgrids with real-time simulation. The recommended controller had high sensitivity to load perturbation. Pan and Das [10] studied fractional order PID controller for distributed AGC to solve the problem caused by the uncertainty of the distributed energy system. Arya and Kumar [11] and Khooban et al. [12] combined fractional order PID controller with fuzzy theory to enhance the robustness of the proposed controller. However, the combinations of different theories will complex the implementation of AGC, especially to large systems. Thus, many other control strategies have been proposed for AGC to improve the practicality such as sliding mode control [13], self-adaptive control [14, 15], robust control [16], and optimal control [17, 18].

Model predictive control (MPC), which performs an optimization procedure to calculate optimal control actions at each sampling interval, is an advanced technology nowadays. MPC has enormous potential for optimal control of the complex system with constraints and has been widely adopted in many industry processes [19–21]. On the one hand, MPC provides satisfactory control performance under dynamic constraints like load reference ramp constraints; on the other hand, it is propitious to the systematic design for multi-input multi-output (MIMO) systems. Therefore, in the research field of AGC, MPC is also an effective alternative method. Ersdal et al. [22] investigated model predictive load-frequency control method with a Kalman filter for state estimation. The research indicated that the MPC controller gives better frequency response while using cheaper resources compared with a PI controller. Jiang et al. [23] proposed model predictive control method in frequency control for an isolated wind-aluminium power system. In order to validate the performances of the previous controller, Jiang et al. [24] made further efforts to introduce explicit MPC for the isolated industrial system. Jang et al. [25] presented an MPC-based approach considering the topology of power grid for AGC so as to improve the dynamic performance of AGC. Taking into account the size of the grid and regional characteristics, Mohamed et al. [26] studied a decentralized model-predictive-based load frequency control method in an interconnected power system. Liu et al. [27] proposed a distributed MPC for a four-area hydrothermal interconnected power system.

Although there are so many approaches that are able to carry out effective automatic generation control, to the best of our knowledge, time delays between different regions are not considered in the vast majority of current research studies. Zhang and Domínguez-García [28] and Pathak et al. [29] discussed the influence of time delay to AGC performance, respectively. Some other scholars think of the time delays as a system constraint in AGC process [11, 30–32]. But the analyses of delays' characteristics and the discussion of delays' processing method are not sufficient in these research studies. For example, two-channel random delays, which are controller-to-actuator (C-A) and sensor-to-controller (S-C) time delays, are not considered. In addition, the differences of time delays between regions of the distributed power systems were not discussed either. Actually, the existence of two-channel delays and differences of time delays between regions are more practical. In our opinion, with the introduction of the smart grid concept, the networked AGC method will gradually be more and more important for secondary frequency control because of its openness, flexibility, and other characteristics. Therefore, it is of great significance to discuss the AGC method with consideration of time delays. Considering the predictive characteristic of MPC and its application in AGC, this paper focuses on the implementation method about how to deal with the influence of two-channel random delays and differences of time delays for AGC based on MPC.

This paper is organized as follows. After introducing the background of the research, the model configurations of multiarea interconnected AGC system and characteristics of MPC are analyzed in Section 2. The analysis is the basis of subsequent description. In Section 3, discretization and influence analysis of time delays are discussed; after that, the principle of control sequence selection with optimization based on DMPC is described. And before providing the conclusions in Section 5, a numerical example is provided in Section 4, which illustrates the effectiveness of the proposed method.

2. AGC System Model with Time Delays

2.1. System Model Building. Generally, a modern power system is a large-scale, geographically dispersed, and complexly interconnected system with distributed generators. A large power system is usually divided into several subsystems which represent interconnected regional power grid for efficient operation and control. The subsystems are connected by the tie-lines. Without loss of generality, a multiarea interconnected power system as shown in Figure 1 is an example for design and analysis purposes. The thermal areas are equipped with single reheat turbine, GRC of 3% per minute and GDB of 0.05%.

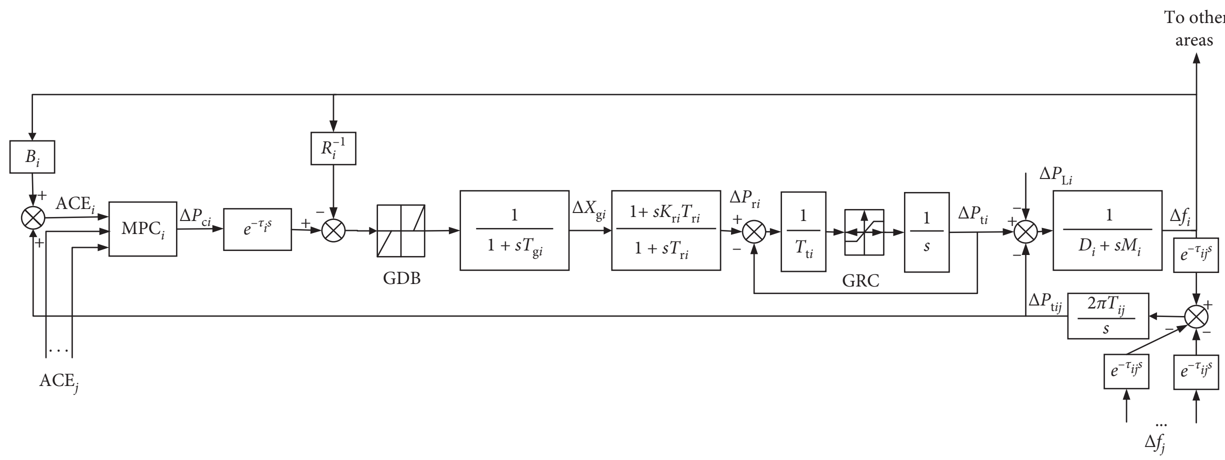


Figure 1: AGC dynamic model with two-channel delays.

Table 1: Notations of variables.

Variables	Notations	Units
T_{gi}	Time constant of the governor for area i	s
T_{ti}	Time constant of the generator for area i	s
K_{ri}	Reheat coefficient of the steam turbine for area i	p.u.
T_{ri}	Reheat time constant for area i	s
R_i	Speed regulation parameter for area i	Hz/p.u.
B_i	Frequency bias factor for area i	p.u./Hz
M_i	Rotary inertia of assembling unit for area i	p.u.s^2
D_i	Damping coefficient of load for area i	p.u./Hz
ΔP_{ti}	Change in turbine output for area i	p.u.
ΔP_{ri}	Change in thermal power output of reheat steam turbine generator sets for area i	p.u.
ΔX_{gi}	Change in valve position of the governor for area i	p.u.
ΔP_{ci}	Control variable of controller for area i	p.u.
ΔP_{Li}	Load changes for area i	p.u.
Δf_i	Frequency deviation for area i	Hz
ΔP_{tij}	Tie-line active power deviation	p.u.
T_{ij}	Power system synchronizing coefficient	s
ACE_i	Area control error for area i	p.u.
τ_i	Controller-to-actuator (C-A) delay	s
τ_{ij}	Sensor-to-controller (S-C) delays among different areas	s
τ_{ca}	Delay from controller to actuator	s
τ_{sc}	Delay from sensor to controller	s

The model of AGC system is built according to the composition and equivalence principle of circuit theory. Two-channel delays are represented by τ_i, τ_{ij}, where τ_i represents controller-to-actuator (C-A) delay, τ_{ij} represent sensor-to-controller (S-C) delays among different areas. The difference of S-C delays indicates that the time delays between different regions are not the same. All the physical meaning and units of variables in this paper are shown in Table 1.

When describing ith regional power grid with subscript i $(i = 1, 2, \ldots, n)$, the state-space equations of each region is given by

$$\begin{aligned}\dot{X}_i(t) &= \mathbf{A}_{ii}X_i(t) + \mathbf{B}_{ii}U(t) + \mathbf{F}_{ii}W_i(t)\\ &\quad + \sum_{i\neq j}\left(\mathbf{A}_{ij}X_j(t) + \mathbf{B}_{ij}U_j(t) + \mathbf{F}_{ij}W_j(t)\right),\\ Y_i(t) &= \mathbf{C}_{ii}X_i(t), \quad i = 1, 2, \ldots, n, \ \ j = 1, 2, \ldots, n,\end{aligned} \tag{1}$$

where $X_i \in R^n, U_i \in R^m, W_i \in R^k, Y_i \in R^r$ are the system state variables, control variables, disturbance variables, and output variables of the ith region, respectively, with appropriate dimensions. $X_j \in R^n, U_j \in R^m, W_j \in R^k, Y_j \in R^r$ are the system state variables, control variables, disturbance variables, and output variables of the jth region adjacent to the ith region. $\mathbf{A}_{ii}$, $\mathbf{B}_{ii}$, $\mathbf{F}_{ii}$, $\mathbf{C}_{ii}$, $\mathbf{A}_{ij}$, $\mathbf{B}_{ij}$, $\mathbf{F}_{ij}$, respectively, are the parameter matrices with appropriate dimensions. In which,

$$
\begin{aligned}
X_i &= \left[\, \Delta f_i \ \ \Delta P_{\mathrm{t}i} \ \ \Delta P_{\mathrm{r}i} \ \ \Delta X_{\mathrm{g}i} \ \ \Delta P_{\mathrm{t}ij} \,\right]^T, \\
Y_i &= \left[\, \mathrm{ACE}_i \ \ \Delta f_i \ \ \Delta P_{\mathrm{t}ij} \,\right]^T, \\
U_i &= [\Delta P_{\mathrm{c}i}], \\
W_i &= [\Delta P_{\mathrm{L}i}], \\
\mathbf{B}_{ii} &= \left[\, 0 \ \ 0 \ \ \tfrac{K_{\mathrm{r}i}}{T_{\mathrm{g}i}} \ \ \tfrac{1}{T_{\mathrm{g}i}} \ \ 0 \,\right]^T, \\
\mathbf{F}_{ii} &= \left[\, \tfrac{-1}{M_i} \ \ 0 \ \ 0 \ \ 0 \ \ 0 \,\right]^T, \\
\mathbf{C}_{ii} &= \begin{bmatrix} B_i & 0 & 0 & 0 & (-1)^{i+1} \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}, \\
\mathbf{A}_{ii} &= \begin{bmatrix} \dfrac{-D_i}{M_i} & \dfrac{1}{M_i} & 0 & 0 & \dfrac{(-1)^i}{M_i} \\ 0 & \dfrac{-1}{T_{\mathrm{t}i}} & \dfrac{1}{T_{\mathrm{t}i}} & 0 & 0 \\ \dfrac{-K_{\mathrm{r}i}}{R_i T_{\mathrm{g}i}} & 0 & \dfrac{-1}{T_{\mathrm{r}i}} & \dfrac{1}{T_{\mathrm{r}i}} - \dfrac{K_{\mathrm{r}i}}{T_{\mathrm{g}i}} & 0 \\ \dfrac{-1}{R_i T_{\mathrm{g}i}} & 0 & 0 & \dfrac{-1}{T_{\mathrm{g}i}} & 0 \\ \sum_j 2\pi T_{ij} & 0 & 0 & 0 & 0 \end{bmatrix}, \\
\mathbf{A}_{ij} &= \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ -2\pi T_{ij} & 0 & 0 & 0 & 0 \end{bmatrix}, \\
\mathbf{B}_{ij} &= \mathbf{B}_{12} = \mathbf{B}_{13} = \mathbf{B}_{21} = \mathbf{B}_{23} = \mathbf{0}_{5\times 1}, \\
\mathbf{F}_{ij} &= \mathbf{F}_{12} = \mathbf{F}_{13} = \mathbf{F}_{21} = \mathbf{F}_{23} = \mathbf{0}_{5\times 1}.
\end{aligned} \tag{2}
$$

Traditional centralized controllers are becoming less reliable and more difficult to deal with the distributed control system considering time delays. The distributed MPC is thus designed based on the system model to maintain the system frequency at the scheduled value.

2.2. Background of Model Predictive Controller. The MPC scheme is based on the system model to obtain the control actions by minimizing an objective function. Considering the following discrete-time system,

$$
\begin{aligned}
x(k+1) &= \mathbf{A}x(k) + \mathbf{B}u(k), \\
y(k) &= \mathbf{C}x(k),
\end{aligned} \tag{3a}
$$

subject to

$$
\begin{aligned}
u_{\min} &= u(k) \le u_{\max}, \\
y_{\min} &\le y(k) \le y_{\max},
\end{aligned} \tag{3b}
$$

where $x \in R^n$, $u \in R^m$ and $y \in R^s$ are the state, input, and output variables, respectively.

The control objective of the controller is to minimize the following cost function:

$$\mathbf{J} = (\mathbf{R}_{\mathrm{S}} - \mathbf{Y})^T (\mathbf{R}_{\mathrm{S}} - \mathbf{Y}), \tag{4}$$

where $\mathbf{R}_{\mathrm{s}}$ is the expected output of the system and $\mathbf{Y}$ is output sequence in prediction horizon.

At each sampling instant, the optimization problem is solved to obtain the optimal control sequence that

$$\mathbf{U}^* = \left[\, u^*(k) \ \ u^*(k+1) \ \ \cdots \ \ u^*(k + N_{\mathrm{c}} - 1) \,\right]^T, \tag{5}$$

where N_{c} is the control horizon and k is the sampling time instant. According to the characteristics of predictive control, only the first value of the control sequence is used during the control process.

Corresponding to the optimal control sequence, the prediction sequence of state variables and output can be obtained as

$$
\begin{aligned}
\mathbf{X} &= \left[\, X(k_i + 1 \mid k_i) \ \ X(k_i + 2 \mid k_i) \ \ \cdots \ \ X(k_i + N_{\mathrm{P}} \mid k_i) \,\right]^T, \\
\mathbf{Y} &= \left[\, Y(k_i + 1 \mid k_i) \ \ Y(k_i + 2 \mid k_i) \ \ \cdots \ \ Y(k_i + N_{\mathrm{P}} \mid k_i) \,\right]^T,
\end{aligned} \tag{6}
$$

where N_{P} is the prediction horizon.

3. Analysis and Processing of Two-Channel Time Delays

3.1. Discretization of Time Delays. Normally, time delay is a random signal, so the priority when time delays exist and are taken under consideration during the control process is discretization. Obviously, time delays have an impact on the control effect only when it is greater than the sampling period. Therefore, according to the value of the delay, the time delay will be discretized into multiple sampling periods. Then, the random delay signal will be modeled as a random Markov jump process [33]. The discretizing process of a delay signal is shown in Figure 2.

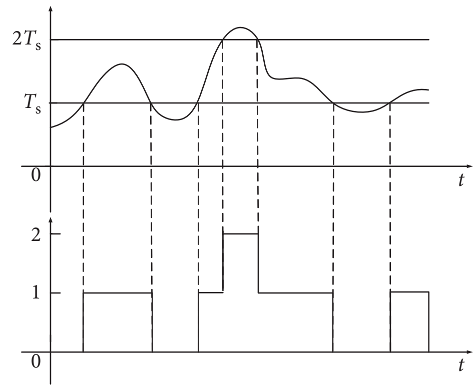


Figure 2: Discretization process of time delay.

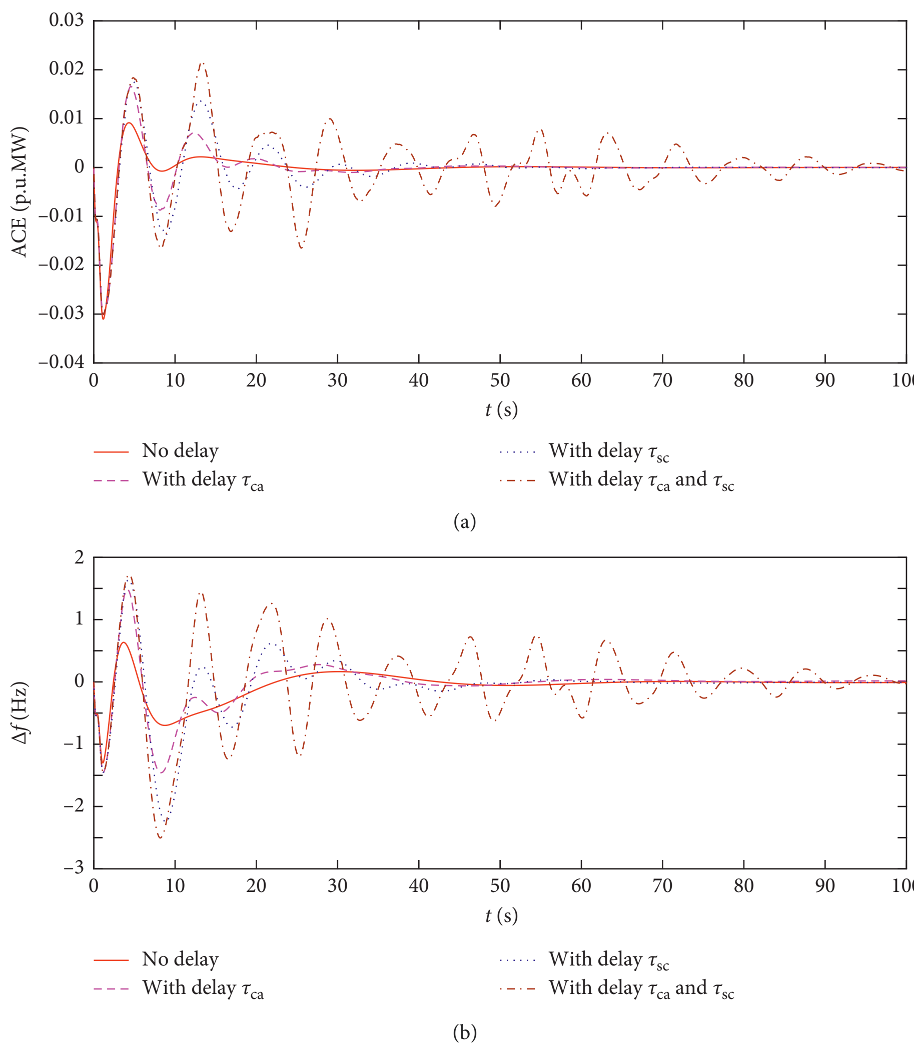
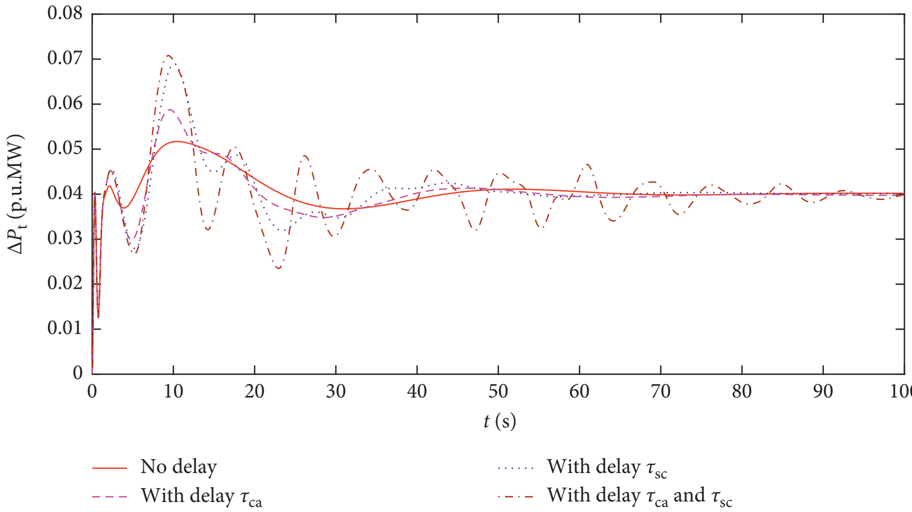


Figure 3: Continued.



(c)

Figure 3: Output response curves under four kinds of delays. (a) ACE response curve. (b) Δf response curve. (c) ΔP_t response curve.

3.2. Influence Analysis of Time Delays. The control process is different to the conventional control state when time delays exist. Focusing on the cases under no delay, single channel delay, and two channel delays, the existing time delays have four states, which are no delay, delay from controller to actuator τ_{ca}, delay from sensor to controller τ_{sc}, and delays τ_{ca} and τ_{sc} existing simultaneously. The differences of time delays between areas are reflected by means of different random delay signals given in the simulation process. Supposing the load change of the area is 0.04 pu step perturbation, the output response can be obtained as in Figure 3.

The output responses from these figures indicate that the control performance of AGC system will deteriorate when considering the channel delays. With channel delays, the output will be oscillating and even not be able to be stable, especially when two-channel delays exist. Therefore, in order to achieve the desired control performance, the influence of the channel delay cannot be ignored.

3.3. The Obtainment of Control Variable considering the Difference of Delays. To mitigate the negative influence of time delays, a buffer could be used to store the latest data. These data have the most recent time stamp in order to get the absent control variable caused by the delay. The absent control variable is reacquired through the calculation depending on the latest data based on MPC.

Once there is a time delay during the information transmission, the controller will not receive the original feedback signal in time and thus cannot generate an appropriate control signal. In this case, the control signal can be reacquired according to the predictive characteristic of MPC. As shown in Figure 4, the control sequence is composed of the executed control signal of current sampling instant and predictive control signals of subsequent sampling instants. Accordingly, the predictive control signals of subsequent sampling instants can be selected as the executed control signal, corresponding to the sampling instant of

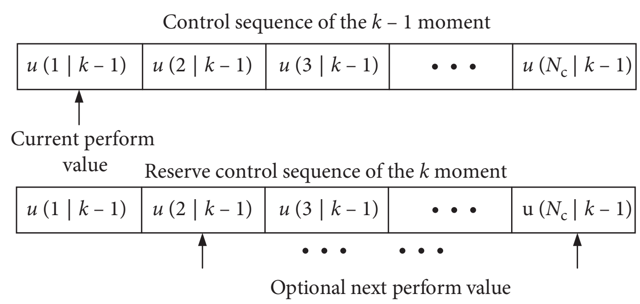


Figure 4: Schematic diagram of predictive control variables.

which information is delayed during communication process. The definite control signal is selected according to the value of two-channel time delays. The value of the system delay is the value sum of S-C and C-A delays. For example, when S-C and C-A delay is 2 and 1 respectively, the value to be processed of the system delay is 3.

The selection process of control signal is shown in Figure 5. The subscript of predictive control sequence indicates the sampling instant; the superscript of the predictive control sequence indicates the ordinal number of predictive variables. Originally, the superscript of the first variable in the sequence is same as the corresponding sampling instant. And the variable is used as the executed control signal in conventional MPC process. When time delay exists, the relevant control sequence cannot be acquired. Then, the executed control variable can be selected from the predictive control sequence calculated by the latest received data. The reacquired control variable and the one that should be the control signal but lost because of the time delay should have the same superscript.

Generally, a reasonable predictive control signal can be obtained to replace the absent control signal. However, considering some certain control modes such as smooth control, it is possible that the control effect will be better when the control sequence is recalculated according to the

t	Control sequence			
1	$\{u_1^1$	u_1^2	$\cdots$	$u_1^{N_c}\}$
2	$\{u_2^2$	u_2^3	$\cdots$	$u_2^{N_c+1}\}$
$\cdots$		$\vdots$		
k	$\{u_k^k$	u_k^{k+1}	$\cdots$	$u_k^{N_c+k}\}$

Figure 5: Schematic diagram of control variables selection.

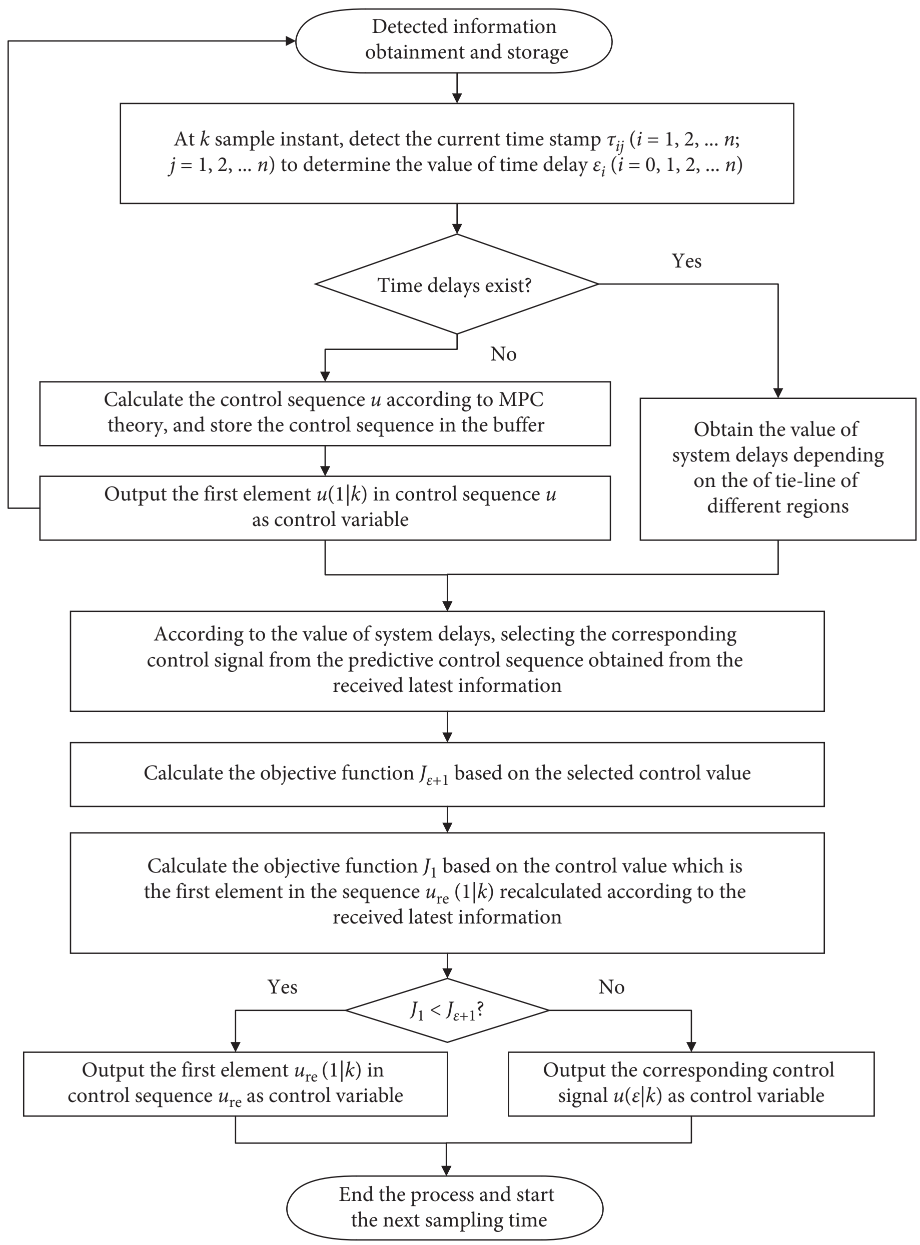


Figure 6: Flow chart of the algorithm.

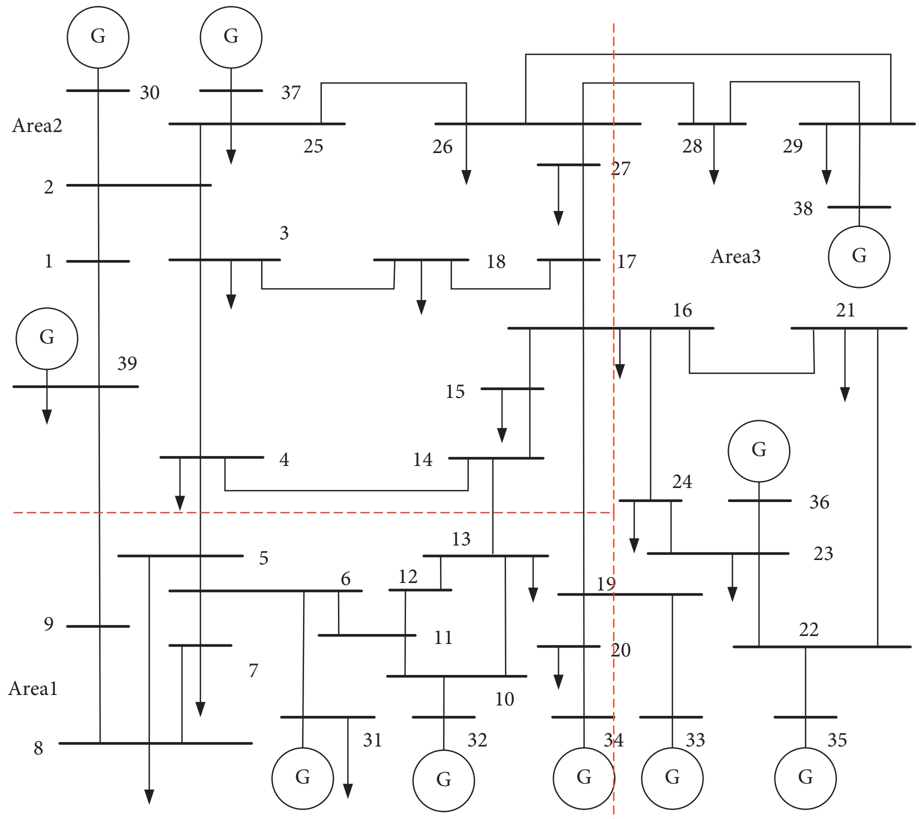


Figure 7: IEEE 39-bus system.

received latest information for the control variables having little change during the control process. Therefore, an optimal strategy is presented to guarantee the best control performance. The optimal algorithm is described in Figure 6.

4. Numerical Example

In this paper, the studied system is simulated based on Matlab/Simulink. The proposed method is tested on the IEEE 39-bus system with 3 areas and 10 machines, as shown in Figure 7.

The studied system is simulated based on Matlab/Simulink to discuss the effectiveness of the proposed method. A three-area AGC system considering two-channel random delay is constructed. The controller is realized by means of MPC toolbox, the prediction horizon N_P is set to 10, control horizon N_c is set to 4, and simulation sampling period is set to 0.01 s. Detailed parameters are shown in Table 2.

Considering two-channel delays, three methods are applied to compare the control performance: (a) according to the received latest data, calculate the control sequence by taking the first value as the output of the current control variable. This means no processing for delay during the control process. (b) According to the judgment of the current system delay, the corresponding value of the latest acquired control sequence is selected as the executed control variable. (c) In the second condition, the objective function of the corresponding value and the first element in the control sequence recalculated by the received latest date are compared, and the superior objective function of the control variables is selected as the output.

Table 2: Simulation parameters of dynamic model of three-area interconnected AGC system.

Parameter	Area 1	Area 2	Area 3	Units
M_i	11	12.5	12	p.u.s^2
D_i	2.75	2.0	2.5	p.u./Hz
B_i	28	19	22.5	p.u./Hz
R_i	0.04	0.06	0.05	Hz/p.u.
K_{ri}	0.3	0.4	0.375	p.u.
T_{gi}	0.15	0.1	0.1	s
T_{ri}	11	9	8	s
T_{ti}	0.2	0.3	0.35	s
T_{ij}	0.85	0.85	0.85	s

Compare the system dynamics of the following three cases assuming the step load perturbationΔP_{L1} is 0.04 pu, ΔP_{L2} is 0.01 pu, and ΔP_{L3} is 0.02 pu: (*a*) no processing for delay; (*b*) control sequence selection; and (*c*) control sequence selection with optimization which is proposed in this paper. The output response of the three areas is shown in Figure 8.

The results indicate that the system is stable in cases *b* and *c*, and case *c* has better performance in settling time and overshoot if time delays exist, while the output curves in case *a* have not only poor transient response but also obvious oscillation and instability.

Random load perturbation is also applied in the three areas to verify the effectiveness of the proposed method. The

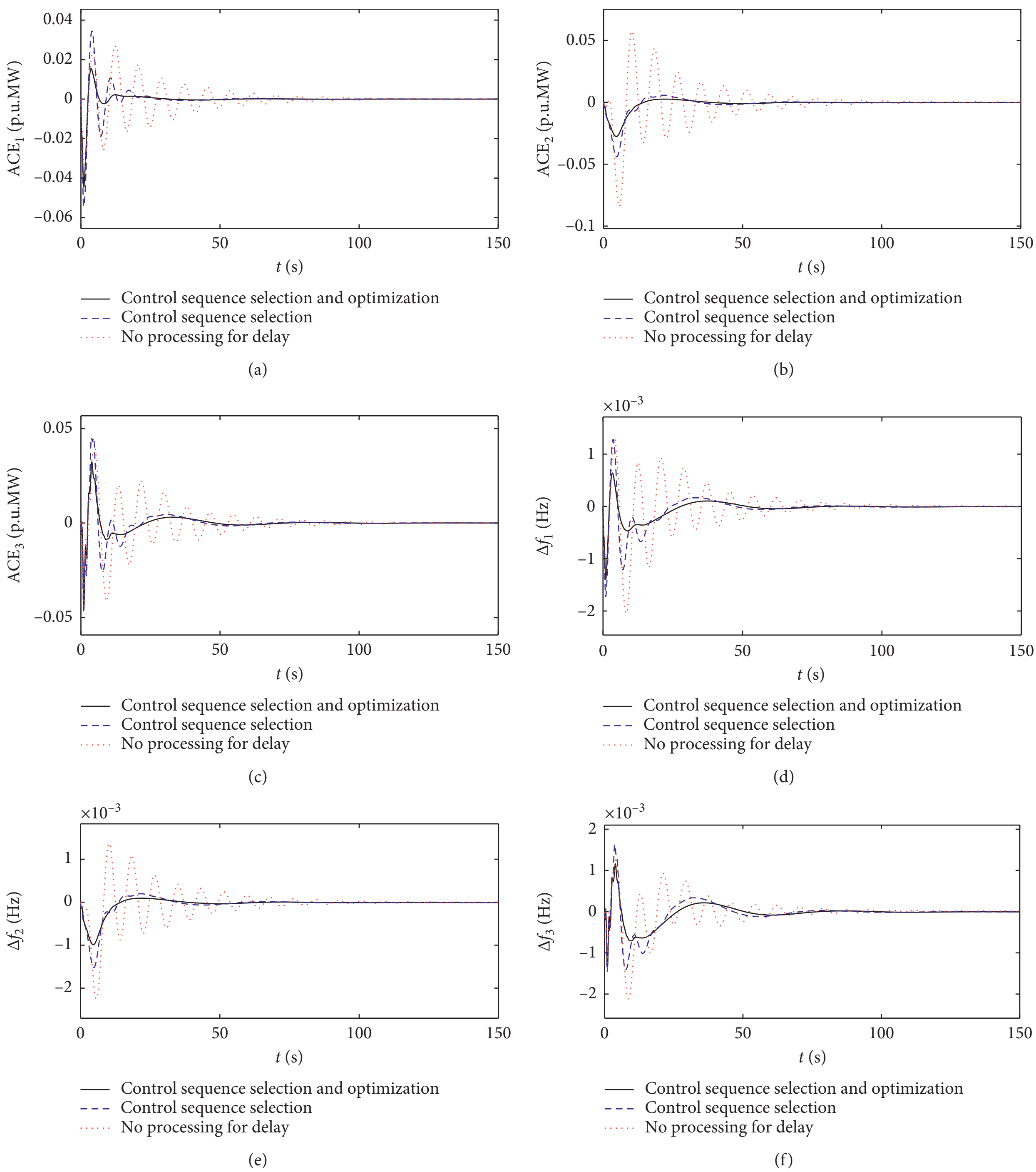


Figure 8: Continued.

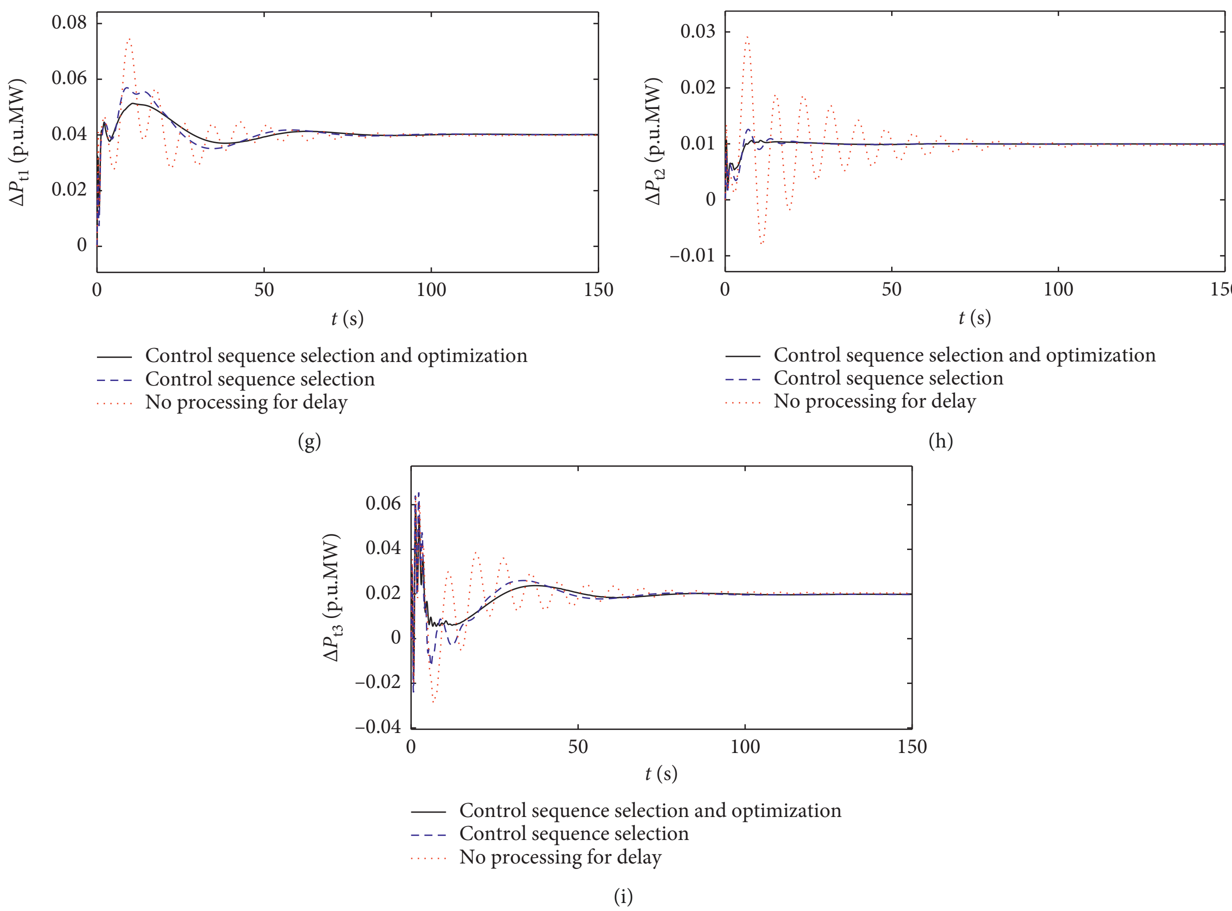


Figure 8: The step response curves. (a) ACE_1 response curve. (b) ACE_2 response curve. (c) ACE_3 response curve. (d) Δf_1 response curve. (e) Δf_2 response curve. (f) Δf_3 response curve. (g) ΔP_{t1} response curve. (h) ΔP_{t2} response curve. (i) ΔP_{t3} response curve.

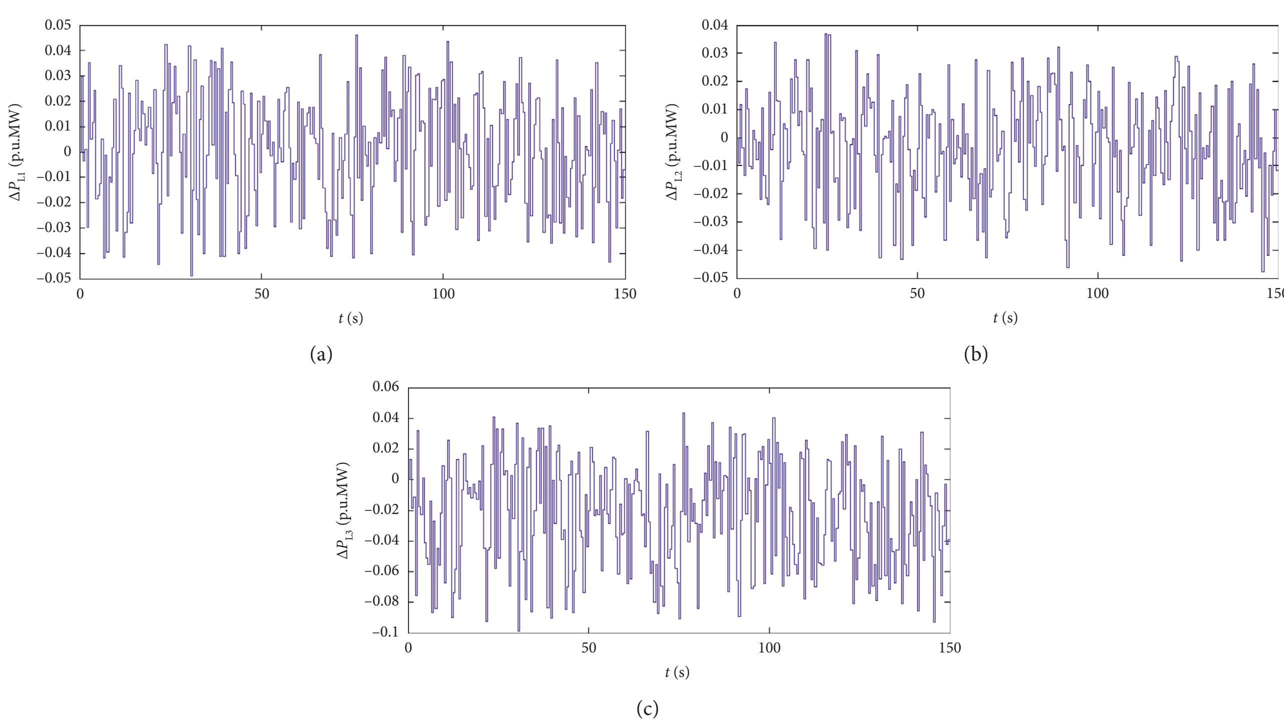


Figure 9: Random input signals. (a) Random input signal ΔP_{L1}. (b) Random input signal ΔP_{L2}. (c) Random input signal ΔP_{L3}.

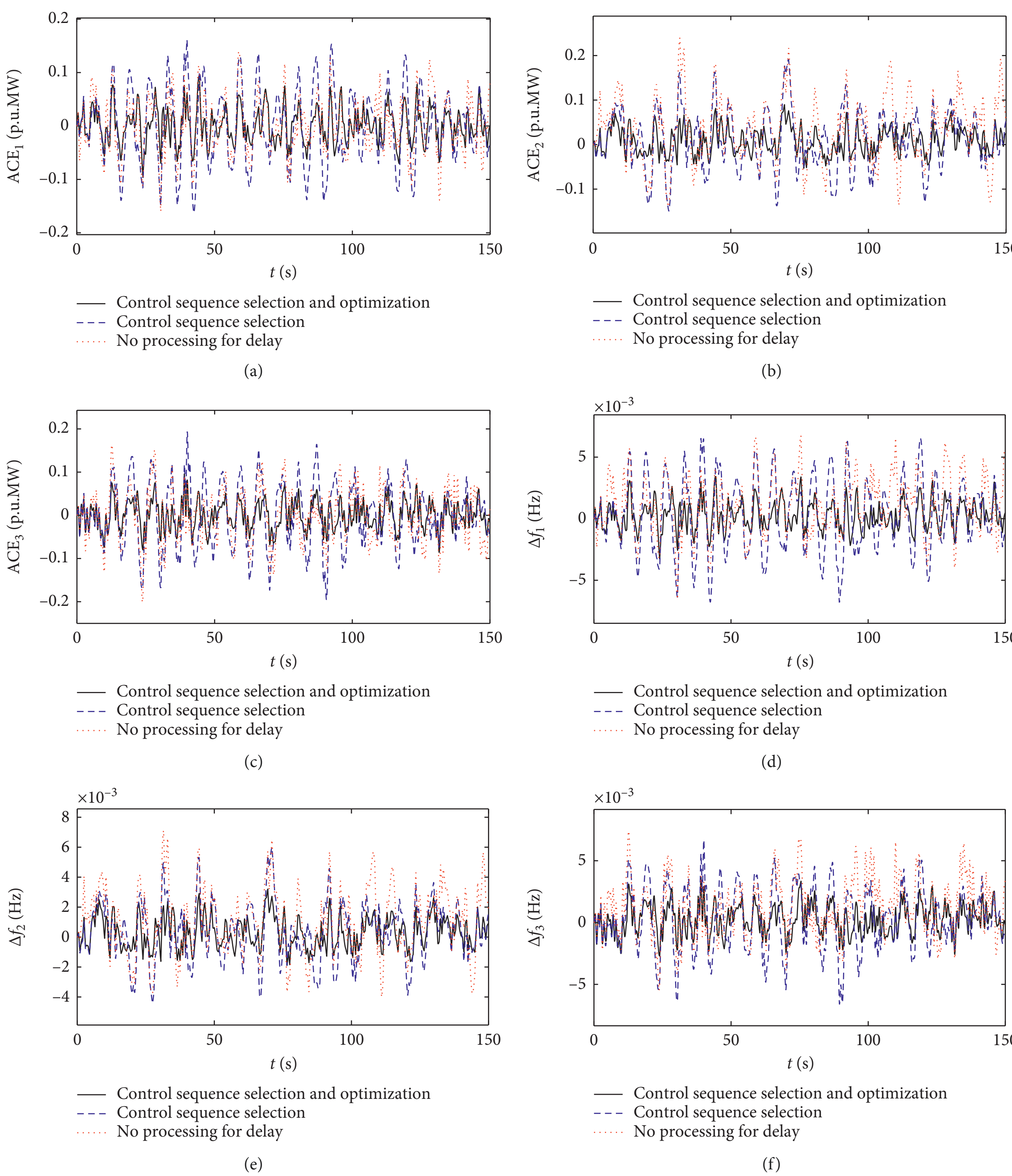
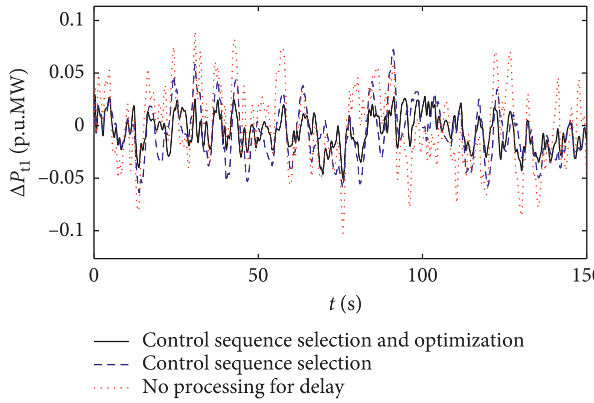
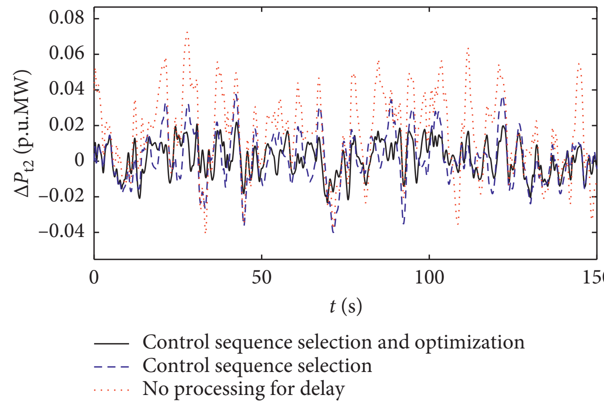


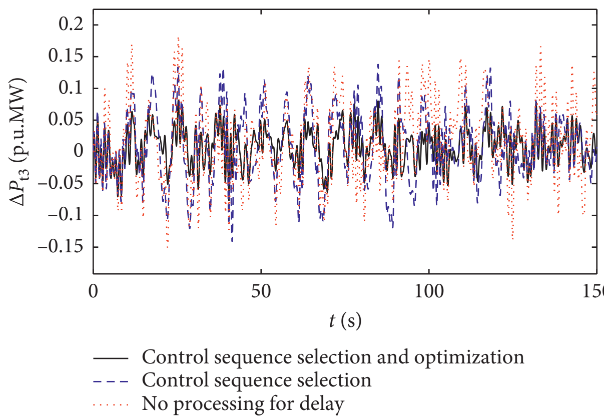
Figure 10: Continued.



(g)



(h)



(i)

Figure 10: Response curves under random signal. (a) ACE_1 response curve. (b) ACE_2 response curve. (c) ACE_3 response curve. (d) Δf_1 response curve. (e) Δf_2 response curve. (f) Δf_3 response curve. (g) ΔP_{t1} response curve. (h) ΔP_{t2} response curve. (i) ΔP_{t3} response curve.

random load perturbation applied in the three areas is shown in Figure 9, and the system dynamic responses are shown in Figure 10.

Figure 10 reveals that the fluctuation around zero has the least amplitude in case c, which means the frequency of system, with the random input, is in the most stable state when the proposed method is applied.

The measurement of two-channel random time delays is essential for the implementation of the proposed method. If the delays are taken into account in the control process, a further discussion of incorporating both forward C-A and feedback S-C delays into controller requires the consideration on the availability of the C-A delay information at the controller node in practical AGC system. Then, an embedded processor needs to be designed to obtain the delay from controller to actuator τ_{ca}. Although the obtaining process has sacrificed a little bit of efficiency compared with ideal condition, the simulation results will still conform to the control performance standard (CPS) of China. Therefore, the proposed method has great potential to be applied in real applications.

5. Conclusion

In this paper, a distributed model predictive AGC method is presented for the multiarea power systems with two-channel random time delays. As an example, a three-area interconnected power system model is built. The building of the system model takes into account not only the two-channel random delays but also the differences of time delays between areas. Based on the predictive characteristic of MPC, a novel method is proposed to mitigate the negative effects of the delays. When time delays exist, the control variable is obtained through a selection and optimization process depending on the predictive control sequence acquired from the received latest data. Three cases corresponding to no processing for delay, control sequence selection, and control sequence selection with optimization are analyzed. Dynamic responses pertaining to the proposed method for AGC show better performance in terms of settling time, overshoot, and oscillations compared to the other two cases, which verifies the feasibility and effectiveness of the proposed method.

Data Availability

Figures 4 and 5 and Table 2 data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The research team members thank the National Natural Science Foundation of China (Grant no. 61473116) and the Scientific Research Foundation for the Returned Overseas Chinese Scholars, State Education Ministry (Grant no. [2014]1685) for the support.

References

[1] S. Liu, P. X. Liu, and A. E. Saddik, "Modeling and stability analysis of automatic generation control over cognitive radio networks in smart grids," *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. 45, no. 2, pp. 223–234, 2015.

[2] A. Rahman, N. Sinha, and L. C. Saikia, "AGC of dish-stirling solar thermal integrated thermal system with biogeography based optimised three degree of freedom PID controller," *IET Renewable Power Generation*, vol. 10, no. 8, pp. 1161–1170, 2016.

[3] A. Modirkhazeni, M. H. Almasi, and M. H. Khooban, "Improved frequency dynamic in isolated hybrid power system using an intelligent method," *International Journal of Electrical Power & Energy Systems*, vol. 78, pp. 225–238, 2016.

[4] I. S. Bautista, I. Egido, and E. L. Miguélez, "Performance evaluation of start-up decisions of rapid-start units for AGC," *IEEE Transactions on Power Systems*, vol. 30, no. 6, pp. 3130–3138, 2015.

[5] H. Chavez, R. Baldick, and J. Matevosyan, "The joint adequacy of AGC and primary frequency response in single balancing authority systems," *IEEE Transactions on Sustainable Energy*, vol. 6, no. 3, pp. 959–966, 2015.

[6] M.-H. Khooban, T. Dragicevic, and M. F. Delimar, "Shipboard microgrids: a novel approach to load frequency control," *IEEE Transactions on Sustainable Energy*, vol. 9, no. 2, pp. 843–852, 2018.

[7] R. K. Sahu, S. Panda, and U. K. Rout, "DE optimized parallel 2-DOF PID controller for load frequency control of power system with governor dead-band nonlinearity," *International Journal of Electrical Power & Energy Systems*, vol. 49, pp. 19–33, 2013.

[8] Y. Xu, F. Li, Z. Jin, and M. Hassani Variani, "Dynamic gain-tuning control (DGTC) approach for AGC with effects of wind power," *IEEE Transactions on Power Systems*, vol. 31, no. 5, pp. 3339–3348, 2016.

[9] M. Gheisarnejad and M. H. Khooban, "Secondary load frequency control for multi-microgrids: HiL real-time simulation," *Soft Computing*, pp. 1–14, 2018.

[10] I. Pan and S. Das, "Fractional order AGC for distributed energy resources using robust optimization," *IEEE Transactions on Smart Grid*, vol. 7, no. 5, pp. 2175–2186, 2016.

[11] Y. Arya and N. Kumar, "BFOA-scaled fractional order fuzzy PID controller applied to AGC of multi-area multi-source electric power generating systems," *Swarm and Evolutionary Computation*, vol. 32, pp. 201–218, 2017.

[12] M.-H. Khooban, T. Niknam, M. Shasadeghi, T. Dragicevic, and F. Blaabjerg, "Load frequency control in microgrids based on a stochastic noninteger controller," *IEEE Transactions on Sustainable Energy*, vol. 9, no. 2, pp. 853–861, 2018.

[13] Y. Mi, Y. Fu, C. Wang, and P. Wang, "Decentralized sliding mode load frequency control for multi-area power systems," *IEEE Transactions on Power Systems*, vol. 28, no. 4, pp. 4301–4309, 2013.

[14] D. Apostolopoulou, P. W. Sauer, and A. D. Dominguez-Garcia, "Balancing authority area model and its application to the design of adaptive AGC systems," *IEEE Transactions on Power Systems*, vol. 31, no. 5, pp. 3756–3764, 2016.

[15] M. H. Khooban and T. Niknam, "A new intelligent online fuzzy tuning approach for multi-area load frequency control: self adaptive modified bat Algorithm," *International Journal of Electrical Power & Energy Systems*, vol. 71, pp. 254–261, 2015.

[16] E. Yao, V. W. S. Wong, and R. Schober, "Robust frequency regulation capacity scheduling algorithm for electric vehicles," *IEEE Transactions on Smart Grid*, vol. 8, no. 2, pp. 984–997, 2017.

[17] Y. Arya and N. Kumar, "Optimal control strategy-based AGC of electrical power systems: a comparative performance analysis," *Optimal Control Applications and Methods*, vol. 38, no. 6, pp. 982–992, 2017.

[18] Y. Arya, N. Kumar, and S. K. Gupta, "Optimal automatic generation control of two-area power systems with energy storage units under deregulated environment," *Journal of Renewable and Sustainable Energy*, vol. 9, no. 6, article 064105, 2017.

[19] S. Sajadian and R. Ahmadi, "Model predictive-based maximum power point tracking for grid-tied photovoltaic applications using a Z-source inverter," *IEEE Transactions on Power Electronics*, vol. 31, no. 11, pp. 7611–7620, 2016.

[20] F. Oldewurtel, A. Parisio, C. N. Jones et al., "Use of model predictive control and weather forecasts for energy efficient building climate control," *Energy and Buildings*, vol. 45, no. 2, pp. 15–27, 2012.

[21] X. Chen, M. Heidarinejad, J. Liu, and P. D. Christofides, "Distributed economic MPC: application to a nonlinear chemical process network," *Journal of Process Control*, vol. 22, no. 4, pp. 689–699, 2012.

[22] A. M. Ersdal, L. Imsland, and K. Uhlen, "Model predictive load-frequency control," *IEEE Transactions on Power Systems*, vol. 31, no. 1, pp. 777–785, 2016.

[23] H. Jiang, J. Lin, Y. Song, and D. J. Hill, "MPC-based frequency control with demand-side participation: a case study in an isolated wind-aluminum power system," *IEEE Transactions on Power Systems*, vol. 30, no. 6, pp. 3327–3337, 2015.

[24] H. Jiang, J. Lin, Y. Zong, S. You, and Y. Song, "Explicit model predictive control applications in power systems: an AGC study for an isolated industrial system," *IET Generation, Transmission & Distribution*, vol. 10, no. 4, pp. 964–971, 2016.

[25] Y.-S. Jang, J. Park, and Y. Yoon, "Designing structure-dependent MPC-based AGC schemes considering network topology," *Energies*, vol. 8, no. 5, pp. 3437–3454, 2015.

[26] T. H. Mohamed, H. Bevrani, A. A. Hassan, and T. Hiyama, "Decentralized model predictive based load frequency control in an interconnected power system," *Energy Conversion and Management*, vol. 52, no. 2, pp. 1208–1214, 2011.

[27] X. Liu, X. Kong, and K. Y. Lee, "Distributed model predictive control for load frequency control with dynamic fuzzy valve position modelling for hydro-thermal power system," *IET Control Theory & Applications*, vol. 10, no. 14, pp. 1653–1664, 2016.

[28] J. Zhang and A. D. Domínguez-García, "On the impact of communication delays on power system automatic generation control performance," in *Proceedings of the 2014 North American Power Symposium (NAPS)*, pp. 1–6, Pullman, WA, USA, September 2014.

[29] N. Pathak, T. S. Bhatti, A. Verma et al., "Real-time automatic generation control considering communication delays using linear matrix inequalities," in *Proceedings of the 2016 IEEE 6th*

International Conference on Power Systems (ICPS), pp. 1–6, New Delhi, India, March 2016.

[30] R. K. Sahu, S. Panda, and S. Padhan, "A hybrid firefly algorithm and pattern search technique for automatic generation control of multi area power systems," *International Journal of Electrical Power & Energy Systems*, vol. 64, pp. 9–23, 2015.

[31] Y. Arya, N. Kumar, and A. Ibraheem, "AGC of a two-area multi-source power system interconnected via AC/DC parallel links under restructured power environment," *Optimal Control Applications and Methods*, vol. 37, no. 4, pp. 590–607, 2015.

[32] M.-H. Khooban, "Secondary load frequency control of time-delay stand-alone microgrids with electric vehicles," *IEEE Transactions on Industrial Electronics*, vol. 65, no. 9, pp. 7416–7422, 2018.

[33] Y. Shi and B. Yu, "Robust mixed H2/H∞ control of networked control systems with random time delays in both forward and backward communication links," *Automatica*, vol. 47, no. 4, pp. 754–760, 2011.