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ORIGINAL RESEARCH

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Age-of-information-aware PI controller for load frequency control

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Abstract

Open communication system in modern power systems brings concern about information staleness which may cause power system frequency instability. The information staleness is often characterized by communication delay. However, communication delay is a packet-centered metric and cannot reflect the requirement of information freshness for load frequency control (LFC). This paper introduces the age of information (AoI), which is more comprehensive and informative than the conventional communication delay modeling method. An LFC controller and communication are integrated into the design for LFC performance improvement. An AoI-aware LFC model is formulated first, and considering each allowable update period of the smart sensor, different AoI-aware PI controllers are then designed according to the exponential decay rate. The right AoI-aware controller and update period are selected according to the degree of frequency fluctuation of the power system. Case studies are carried out on one-area and two-area power systems. The results show the superior performance of the AoI-aware controllers in comparison to the delay-dependent controllers.

Keywords Power system, Load frequency control (LFC), Age of information (AoI), PI controller

1 Introduction

Load frequency control (LFC) is one of the fundamental applications of the cyber-physical power system [1, 2]. LFC aims to maintain frequency and power interchanges with neighborhood areas at scheduled values by regulating generation units [3, 4]. LFC works in a sampled-data form due to the discrete information update process and continuous physical plant operation process. The information update process involves smart sensors, communication system, and control center. The information is updated by smart sensors and is transmitted through the communication system to the control center. The information update process inevitably increases information staleness, especially in the open communication system widely used in LFC [5]. However, severe information staleness may threaten the frequency stability of a power system [4, 6, 7].

Communication delay is often applied to the LFC study to characterize the information staleness [8]. To deal with the delay-constrained LFC problem, the previous studies on the stabilization of power system frequency are mainly from two perspectives: the modeling of communication delay and the design of the controller [9]. For example, delay-dependent stability for a traditional LFC scheme with constant and time-varying delays is investigated in [10], while a delay-dependent robust controller is studied in [11]. In addition, there are different LFC algorithms, such as robust decentralized PI-based LFC [12–14], decentralized sliding-model LFC [15], active disturbance rejection control [16], model-based control [17] and model predictive control [8]. However, most of these advanced methods suggest complex state feedback or high-order dynamic controllers. As shown in [18], power systems still prefer conventional PI controllers. However, the communication delay is not the optimal

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metric to describe the information staleness [19]. Communication delay is an information-packet-centered metric. It overlooks the control factors of the update process such as the update period, the routing selection, and the retransmission mechanism [20]. Therefore, it cannot provide the controllability of the communication system. Therefore, the above delay-dependent controllers may be conservative and cannot provide good solutions for the LFC performance based on the delay model [18].

This paper introduces the age of information (AoI) to the LFC study to characterize the information staleness, and to capture the randomness of state updates [19, 21]. AoI is the length of time that elapsed from the generation of the most recently delivered packet [22], and contains richer connotations than communication delay, including the effects of the control factors of the information update process. In this study, an AoI-aware method is made to couple the LFC controller and communication as an integrated entity, which is called as AoI-aware controller.

This paper consider the control factors of the information update process and the information update period, to show the design process. With the right update period, the control center can receive fresher information and make better decisions to regulate the output of generation units. Thus, the LFC performance is improved. Compared with the communication delay, AoI is more accurate to describe the information staleness. The proposed AoI-aware controller shows superiority to stabilize the power system theoretically.

The design of the AoI-aware PI controller contains three steps. The AoI-aware LFC model of the power system is formulated first. Different AoI-aware PI-type controllers are then designed for different update periods according to the exponential decay rate (EDR). The values of EDR are adjusted by the performance evaluation conditions of parameter $H\infty$ performance. Finally, a right AoI-aware PI-type controller and update period are selected according to the degree of frequency fluctuation of the power system because the optional update period is relatively limited in practical power systems [4, 23].

The Main contributions of this paper are:

1. Formulate an AoI-aware LFC model, and AoI is used instead of communication delay to describe the information update process in the LFC.
2. Design an AoI-aware PI controller to improve LFC performance. The LFC controller and the communication are integrated as a single design entity.

Reference [24] introduces the AoI in the communication area to describe the information staleness of LFC and optimizes the controller parameters from the perspective of the information update process. The main differences in novelty, analysis, and case study parts between [24] and this paper can be summarized as follows.

- For novelty, the role of AoI in [24] is to alleviate the effect of limited communication bandwidth, whereas in this paper it is used to stress the information staleness issues for LFC. The difference between AoI and communication delay is elaborated, while [24] designs an LQR controller for the LFC system, this paper designs a PI controller. Compared with the complicated LQR controller, the PI controller is much simpler and easier to implement in practice.
- For the analysis of LFC models, reference [24] employs the event-triggered communication mechanism while this paper uses the time-triggered communication mechanism. Different communication mechanisms involve different analyses and models. Besides, this paper considers operating points and practical nonlinear constraints, including the GRC and GDB constraints. However, these nonlinear constraints are simplified in [24], which makes its model limited.
- For the case study, this paper considers the scenarios under the nonlinear GRC and GDB constraints and different operating points while [24] does not study such conditions.

The remainder of this paper is organized as follows. Section 2 includes the structure of the communication system and the AoI model, while Sect. 3 proposes the AoI-aware LFC model and introduces the design process of the AoI-aware PI controller. Section 4 presents the results of one-area and two-area AoI-aware LFC performances, and compares the abilities of delay-dependent PI controllers and AoI-aware PI controllers. Finally, Sect. 5 concludes this paper.

2 Problem formulation

This section describes the communication process for LFC, gives the comparison between communication delay and AoI, and presents the metric descriptions.

2.1 Communication process for LFC

LFC aims to maintain the frequency stability and the tie-lie power exchange in a scheduled value. Figure 1 illustrates the equivalent model of the ith area LFC system. It includes the communication system and the physical power system. The communication system samples the area control error (ACE) message and generates the control command $u(t_k)$ to govern the output of generation unit $\Delta P_{\mathrm{m}i}$. The ACE of the ith area,

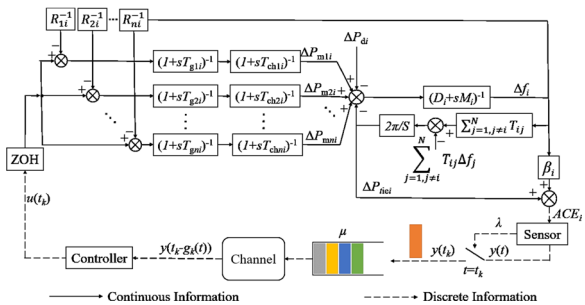

Fig. 1 A dynamic model of the *i*th area LFC system

denoted as ACE_i, is the combination of the frequency deviation Δf_i and net exchange power deviation $\Delta P_{\text{tie}i}$, i.e.:

$$ACE_i = \beta_i \Delta f_i + \Delta P_{\text{tie}i} \tag{1}$$

where β_i is the frequency deviation factor.

The sensors, such as remote terminal units (RTUs), sample the area control error signal ACE_i at t_k. The sensor updating information interval is called update period λ. Then, the sampled packets $y(t_k)$ are queuing in front of the communication channel for transmission. Subsequently, $y(t_k)$ is transmitted through the communication channel and is received by the controller. The controller receiving information rate is called service rate μ. Information staleness will rise in the communication process [7, 25].

In this paper, the communication process is abstracted as an M/M/1 queue system which means the update rate λ^{-1} obeys the Poisson distribution random process, and the service rate μ obeys the exponential distribution random process. Additionally, the communication process follows a first-come-first-serve (FCFS) principle.

2.2 AoI and communication delay

AoI is first proposed in [10, 26] to measure information freshness at the destination node such as the control center. Note that each information packet includes the time stamp information that indicates the update time and received time of the packet. Define the update time of the information packet as t_k, the AoI $g_k(t)$ at the controller can be defined as [10, 27]:

$$g_k(t) = t - \max\{t_k | t'_k < t\} \tag{2}$$

Figure 2 shows the model of AoI $g_k(t)$ at the controller. Information packet k is updated at time t_k and received at the time. AoI $g_k(t)$, as a function of time t, is jagged. Whenever the controller receives more fresh information, the AoI drops to the next information's communication delay. Otherwise, it grows linearly.

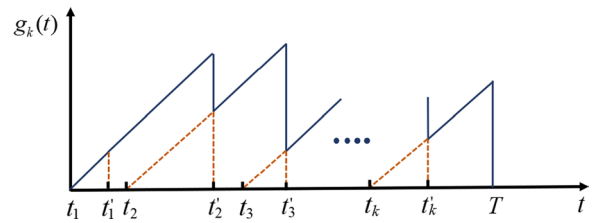

Fig. 2 Example variation in AoI at the controller under FCFS queue

Average AoI is the area under the jagged function in Fig. 2 by the observation interval T. Over the interval (0, T), the average AoI E[$g_k(t)$] is:

$$E[g_k(t)] = \lim_{T\to\infty} \frac{1}{T} \int_0^T g_k(t)dt \tag{3}$$

Considering the FCFS M/M/1 communication system, its average AoI g_{ave} is expressed as:

$$g_{\text{ave}}(\lambda) = \mu + \lambda + \frac{\mu^3}{\lambda^2 - \mu\lambda} \tag{4}$$

It is clear from (4) that the average AoI g_{ave} is related to the updating period λ and service rate μ. To guarantee that the sensors can update their status stably, the region of the update period is $0 < \lambda_{\min} \le \lambda \le \lambda_{\max}$. The service rate is associated with the communication infrastructure and is a constant [19]. The average AoI $g_{\text{ave}}(\lambda)$ can be minimized with respect to the update period λ.

Let the service rate $\mu = 1$ message/second, the update period $\lambda = 1.83$ s, and g_{ave} (1.88) is minimal, the minimized average AoI is obtained by choosing an update period λ that makes the communication channel to be only slightly busier than idle.

Note that $\lambda^{-1} \to \mu$ can achieve maximum throughput and $\lambda \to 0$ can minimize the communication delay. The maximum throughput may cause a large communication delay and the minimization of communication delay will make the control center lack sufficient information for decision-making. Thus, these two methods cannot make information updated freshly.

The period time $t'_k - t_k$ is called the communication delay d_k of information packet k, which includes the queuing time and service time of information packet k [28], as:

$$d_k = t'_k - t_k \tag{5}$$

Table 1 shows the difference between AoI and communication delay in these aspects [29]. Firstly, AoI describes the whole communication process, whereas the conventional communication delay model is usually defined

Table 1 Comparison of AoI and communication delay

Metric	AoI	Delay
Object	The whole information update process	Each information packet
Definition	$g_k(t) = t - \max\{t_k \mid t'_k < t\}$	$d_k = t'_k - t_k$
Model	Communication queue model	Random sequence [18]
Property	Provide the communication system observability and controllability	Cyber contingency

for each information packet. Secondly, AoI employs the communication queue model to model the communication process while the conventional communication delay model is characterized by random sequences. The AoI model is more accurate because the sensor can update the information according to its will. Thirdly, AoI model takes into account the effects of control factors, such as the frequency of information transmission, so that it shows the controllability of the communication system.

2.3 Metric descriptions

The LFC performance metric W, namely, average frequency fluctuation, is introduced first to describe the average frequency fluctuation. Then the EDR m and $H\infty$ gain γ are respectively proposed to describe the frequency convergence with load disturbance $\Delta P_{\mathrm{d}} = 0$ and disturbance rejection capability of the power system with load disturbance $\Delta P_{\mathrm{d}} \neq 0$. W and EDR m are frequency performance metrics, and their difference is that the LFC performance metric W describes not only the frequency convergence but also the amplitude of frequency fluctuation. Generally, the AoI-aware PI controller is designed according to the EDR m and $H\infty$ gain γ. The right AoI-aware controller is then selected by the LFC performance metric W.

The LFC design objective is to improve LFC performance. The LFC performance metric W is defined as:

$$W = \sum_{i=1}^{N} \frac{\int_0^T |\Delta f_i| dt}{T} \tag{6}$$

where T is the observed time, Δf_i is the frequency deviation of the ith area. Small W means that power system frequency can converge to stable value quickly and smoothly. The average frequency fluctuation W can be minimized by the integration design of the update period and LFC controller.

The EDR is introduced as a performance metric to describe the controller's robustness and frequency response dynamic performance. It can vary in the interval $[0, \infty)$. When EDR $m \to 0$, the robustness becomes the strongest, and the dynamic frequency response performance becomes the worst. When EDR $m \to \infty$, the robustness becomes the weakest, but the frequency response dynamic performance is considered to be the best.

$H\infty$ gain γ describes the disturbance suppression capability of a power system, and the small $H\infty$ gain γ means strong disturbance suppression ability.

The design of the AoI-aware PI controller contains three steps. The AoI guides first choose the update period of the communication system. A right update period decides a small AoI, which means the PI controller can receive fresher information and then change the units to stabilize the frequency more quickly. The EDR is then introduced to guide the design of an AoI-aware PI controller. The values of EDR are adjusted by the given robust performance evaluation conditions of $H\infty$ performance. Finally, the right AoI-aware PI controller is selected by the LFC performance metric W.

3 Design of AoI-aware PI controller

This section formulates the AoI-aware LFC model and proposes the AoI-aware PI controller.

3.1 AoI-aware LFC model

Considering the multi-area power system depicted in Fig. 1, the generation units are equivalent to the model of the governor and turbine. In this paper, the model of a non-reheating steam turbine generator unit with a governor is considered, and its transfer function is $1/[(1+sT_{\mathrm{g}i})(1+sT_{\mathrm{ch}i})]$, where $T_{\mathrm{g}i}$ and $T_{\mathrm{ch}i}$ represent the governor time constant and steam turbine time constant, respectively.

The frequency dynamics can be linearized for small-signal stability analysis:

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) + F\Delta P_{\mathrm{d}} \ (a) \\ y(t) = Cx(t) \ (b) \end{cases} \tag{7}$$

where

$$x_i(t) = \left[\Delta f_i \ \Delta P_{\mathrm{m}i} \ \Delta P_{\mathrm{v}i} \ \int ACE_i \ \Delta P_{\mathrm{tie}i}\right]^T$$

$$y_i(t) = \left[ACE_i \ \int ACE_i\right]^T, \ B_i = \left[0 \ 0 \ \frac{\alpha_i}{T_{\mathrm{g}i}} \ 0 \ 0\right]^T$$

$$A_{ii} = \begin{bmatrix} -\frac{D_i}{M_i} & \frac{1}{M_i} & 0 & 0 & -\frac{1}{M_i} \\ 0 & -\frac{1}{T_{\mathrm{ch}i}} & \frac{1}{T_{\mathrm{ch}i}} & 0 & 0 \\ -\frac{1}{R_i T_{\mathrm{g}i}} & 0 & -\frac{1}{T_{\mathrm{g}i}} & 0 & 0 \\ \theta_i & 0 & 0 & 0 & 1 \\ \sum_{j=1, j\neq i}^{n} T_{ij} & 0 & 0 & 0 & 0 \end{bmatrix}, \ A_{ij} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ -Tij & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$F_i = \begin{bmatrix} -\frac{1}{M_i} & 0 & 0 & 0 \end{bmatrix}^T,\ C_i = \begin{bmatrix} \beta_i & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix}$$

Define that $x(t) = [x_1(t)\ x_2(t)\ \ldots\ x_n(t)]^{\mathrm{T}}$, $y(t) = [y_1(t)\ y_2(t)\ \ldots\ y_n(t)]^{\mathrm{T}}$, $u(t) = [u_1(t)\ u_2(t)\ \ldots\ u_n(t)]^{\mathrm{T}}$, and $\Delta P_{\mathrm{d}}(t) = [\Delta P_{\mathrm{d1}}(t)\ \Delta P_{\mathrm{d2}}(t)\ \ldots\ \Delta P_{\mathrm{d}n}(t)]^{\mathrm{T}}$, where $x_i(t)$, $y_i(t)$, $u_i(t)$, $\Delta P_{\mathrm{d}i}(t)$ represent the state vector, the output of the sensor, the output of the control center, load deviation of the ith area, respectively. Define the system matrix $A = [A_{ij}]_{n\times n}$, the control matrix $B = \mathrm{diag}[B_1 B_2\ \ldots B_n]$, the output matrix $C = \mathrm{diag}[C_1 C_2\ \ldots C_n]$, the disturbance matrix $F = \mathrm{diag}[F_1 F_2\ \ldots\ F_n]$. $\Delta P_{\mathrm{m}i}$ and $\Delta P_{\mathrm{v}i}$ represent the generator mechanical power output deviation and control valve position deviation of the ith area LFC power systems, respectively. In addition, T_{ij} is the synchronization factor of the contact line between area i and area j, where $T_{ij} = T_{ji}$.

The ACE_i acts as the input of the PI controller. The information staleness of the ACE messages herein is characterized by AoI $g_{ki}(t)$, where $g_{ki}(t)$ represents the AoI of the kthACE_i at the controller at the time t in the ith area LFC. Based on (7b), the output of the LFC controller can be expressed as:

$$\begin{aligned} u_i(t) &= -K_{\mathrm{P}i}ACE_i - K_{\mathrm{I}i}\int ACE_i \\ &= -K_i y_i\big(t - g_{ki}(t)\big) \\ &= -K_i C_i x_i\big(t - g_{ki}(t)\big) \end{aligned} \tag{8}$$

where $K_i = [K_{\mathrm{p}i} K_{\mathrm{I}i}]$.

The multi-area closed-loop AoI-aware LFC system can be expressed as:

$$\dot{x}(t) = Ax(t) + \sum_{i=1}^{n} A_{\mathrm{d}i}x\big(t - g_{ki}(t)\big) + F\Delta P_{\mathrm{d}} \tag{9}$$

Defining $A_{\mathrm{d}i} = [0\ldots\text{-}B_i K_i C_i\ldots 0]$ and assuming each area has the same AoI with $g_{k1}(t) = g_{k2}(t) = \ldots = g_{kn}(t) = g_k(t)$, there is:

$$\dot{x}(t) = Ax(t) + \sum_{i=1}^{n} A_{\mathrm{d}i}x\big(t - g_k(t)\big) + F\Delta P_{\mathrm{d}} \tag{10}$$

The discrete-time representation of multi-area AoI-aware LFC model can be expressed as:

$$\begin{aligned} \dot{x}(t) &= Ax(t) + \sum_{i=1}^{n} A_{\mathrm{d}i}x\big(t_k - g_k(t)\big) + F\Delta P_{\mathrm{d}} \\ t_k &< t < t_{k+1} \end{aligned} \tag{11}$$

3.2 Design of an AoI-aware PI-type controller

In this part, the AoI-aware PI controller can be designed and the right AoI-aware PI controller can be chosen to improve the LFC performance.

EDR is introduced first to guide the design of the AoI-aware PI controller shown in Theorem 1. This step guarantees that the LFC system (11) is exponentially stable and has EDR m. Next, the $H\infty$ gain γ metric is introduced to evaluate the EDR of the designed controller with non-zero load disturbance shown in Condition 1. The values of EDR can be adjusted by $H\infty$ performance, which describes the disturbance rejection capability of the power system while ensuring the frequency convergence rate. Meanwhile, Algorithms 1 and 2 are respectively proposed to introduce the process of AoI-aware PI controller design.

Theorem 1 [9]: *Consider AoI-aware LFC system* (11) *with zero load disturbance $\Delta P_d = 0$. When given average AoI $g_{ave}(\lambda)$, EDR m and turning parameters l_1 and l_2, existing symmetric positive definite matrices P_1, P_3 and symmetric matrices P_2, Z, and any appropriately dimensioned matrices X_1, X_2, S, Y, and R_2 satisfy the following inequalities*:

$$\Theta_{1j} = \varphi_1 + \Gamma_j + \lambda^{-1}\varphi_2 < 0, \quad j = 1, 2 \tag{12}$$

$$\Theta_{2j} = \begin{bmatrix} \varphi_1 + \Gamma_j & -\lambda^{-1}\psi_2^T R_2 \\ * & -\lambda^{-1}Z \end{bmatrix} < 0 \tag{13}$$

$$\begin{aligned} \varphi_1 = Sym\left\{ \begin{bmatrix} c_1 \\ c_3 \end{bmatrix}^T P_1 \begin{bmatrix} c_5 \\ c_4 \end{bmatrix} + \psi_2^T R_2(c_1 - c_2) \right\} \\ - \begin{bmatrix} c_3 \\ c_2 \end{bmatrix}^T X \begin{bmatrix} c_3 \\ c_2 \end{bmatrix} + \begin{bmatrix} c_1 \\ c_5 \end{bmatrix}^T P_2 \begin{bmatrix} c_1 \\ c_5 \end{bmatrix} - \begin{bmatrix} c_3 \\ c_4 \end{bmatrix}^T P_2 \begin{bmatrix} c_3 \\ c_4 \end{bmatrix} \\ + g_{\mathrm{ave}}(\lambda)c_5^T P_3 c_5 - \frac{1}{g_{\mathrm{ave}}(\lambda)}(c_1 - c_3)^T P_3(c_1 - c_3) \end{aligned}$$

$$\Gamma_j = \psi_1^T \psi_3\Big(S^T c_5 - (A_{ii} + mI)S^T c_1 - \eta_j B_i Y c_2\Big)$$

$$X = \begin{bmatrix} X_1 + X_1^T & -X_1 - X_2 \\ (-X_1 - X_2)^T & X_2 + X_2^T \end{bmatrix}$$

$$\varphi_2 = c_4^T Z c_4 + Sym\left\{ \begin{bmatrix} c_3 \\ c_2 \end{bmatrix}^T X \begin{bmatrix} c_4 \\ 0 \end{bmatrix} \right\}$$

$$c_\varepsilon = \left[0_{\zeta\times(\varepsilon-1)\zeta}\ I_\zeta\ 0_{\zeta\times(5-\varepsilon)\zeta}\right], \varepsilon = 1,\ldots,5$$

$$\psi_1 = \left[c_1^T\ c_2^T\ c_5^T\right]^T,\ \psi_2 = \left[c_1^T\ c_2^T\ c_3^T\ c_4^T\ c_5^T\right]^T$$

$$\psi_3 = [I; l_1 I; l_2 I],\ \eta_1 = e^{mg_{\text{ave}}(\lambda)},\ \eta_2 = e^{m\left(g_{\text{ave}}(\lambda)+\lambda^{-1}\right)}$$

where ζ is the dimension of the matrix A in (11). Then any AoI smaller than $g_{ave}(\lambda)$ can keep the AoI-aware LFC system stable with EDR m. The control gain of the AoI-aware PI controller can thus be obtained by:

$$K_i = Y\left(S^T\right)^{-1} C_i^T \left(C_i C_i^T\right)^{-1} \tag{14}$$

To evaluate the EDR of the designed controller, $H\infty$ performance analysis is introduced in Condition 1.

Condition 1 Here γ is introduced to present $H\infty$ performance. Considering an AoI-aware LFC system (11) with $\Delta P_\text{d} \neq 0$, when given $H\infty$ gain γ, existing symmetric positive definite matrices P_1, P_3 and symmetric matrices P_2, Z, and any appropriately dimensioned matrices X_1, X_2, R_2, and L satisfy the following inequalities.

$$\Omega_1 = \begin{bmatrix} \Theta_1 & -\psi_1^T L F_i \\ * & -\gamma I \end{bmatrix} < 0 \tag{15}$$

$$\Omega_2 = \begin{bmatrix} \Theta_2 & \begin{bmatrix} -\psi_1^T L F \\ 0 \end{bmatrix} \\ * & -\gamma I \end{bmatrix} < 0 \tag{16}$$

$$\Theta_1 = \varphi_1 + \Gamma + \lambda^{-1}\varphi_2 < 0 \tag{17}$$

$$\Theta_2 = \begin{bmatrix} \varphi_1 + \Gamma & -\lambda^{-1}\psi_2^T R_2 \\ * & -\lambda^{-1} Z \end{bmatrix} < 0 \tag{18}$$

$$\Gamma = Sym\{\psi_1^T L(c_5 - A_{ii}c_1 - B_i K_i C_i c_2)\}$$

Then any AoI smaller than $g_\text{ave}(\lambda)$ can keep the AoI-aware LFC system stable with load disturbance ΔP_d and $H\infty$ gain γ. ${c_1}^T {C_i}^T C_i c_1$ should be added into ϕ_1 and the other matrix notations are the same as Theorem 1. The proof of Condition 1 is given in [30].

The algorithm of design of the AoI-aware PI controller is discussed. For a given allowable average AoI $g_\text{ave}(\lambda_i)$, the following Algorithm 1 is developed to determine the AoI-aware PI controller gains $K_{\text{p}i}$, $K_{\text{I}i}$ with desired EDR, including $H\infty$ gain γ.

Algorithm 1: Find AoI-aware PI-type controller gain K_p, K_I

Given λ, $g_\text{ave}(\lambda)$, γ, and search EDR interval [m_min, m_max] with m_min=0 and sufficiently large m_max, the accuracy coefficient m_ac=0.001.

```
Repeat
    m_test=(m_min+m_max)/2
    If the LMIs (12) and (13) are feasible then
  Compute K_p, K_I by equation (14).
    Bring K_p, K_I into Condition 1 with γ
    Repeat
        If the LMIs (15)-(18) are feasible then
        m_min=m_test
        else
        m_max=m_test
    else
    m_max=m_test
until m_max-m_min<m_ac
Return K_p, K_I
```

Next, Algorithm 2 is proposed to optimize the LFC performance W. W can be minimized by following two steps. The optional update period is relatively limited in practical power systems. The first step is to design the different AoI-aware PI controller gains for each allowed update period according to EDR, while the second step is to find the appropriate AoI-aware PI controller and the update period based on the degree of frequency fluctuation of power system W. The specific process to optimize LFC performance is shown in Algorithm 2.

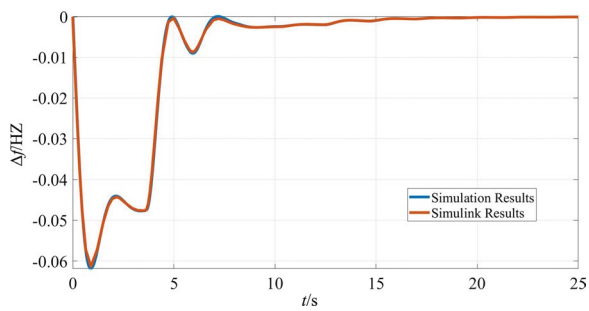

Fig. 3 Comparison of the frequency deviation Δf from the Simulink results and simulation results based on the proposed AoI-aware LFC model under the update period $\lambda = 2.2$ s for $\Delta P_d = 0.02$ pu

Algorithm 2: Minimize the average frequency fluctuation W

Given the allowed update period collection $\lambda = \{\lambda_1, \lambda_2 \ldots \lambda_n\}$ and the observation interval T.

for i=1:n

Compute $g_{ave}(\lambda_i)$ by equation (4) then

Find the AoI-aware PI controller gain K_{pi}, K_{Ii} with the desired EDR by Algorithm 1 then

Compute W_i by the model (6)

end

Return minimum W_s from W_i i=1, 2…n, λ_s, and K_{ps}, K_{Is}.

4 Case study

In this section, the correctness of the AoI-aware LFC model is proved and case studies are carried out on one-area and two-area power systems. The performances of the system with different update periods are evaluated. Additionally, the abilities of the proposed AoI-aware PI controller and delay-dependent PI controller to stabilize the system are compared.

4.1 Prove the correctness of the AoI-aware LFC model

Considering the one-area power system in Table 2, the update period is $\lambda = 2.2$ s, the AoI-aware PI controller gains are $K_p = 0.6952$, $K_I = 0.3752$, and the load disturbance is $\Delta P_d = 0.02$ pu. Figure 3 compares the frequency deviation Δf from the Simulink results and simulation results based on the proposed AoI-aware LFC model. As can be seen from Fig. 3 that the frequency deviation curves are almost the same, which proves the correctness of the AoI-aware LFC model.

4.2 One-area AoI-aware LFC

Considering a one-area AoI-aware LFC system, the system's parameters are reported in Table 2. It assumes that $\alpha_1 = 1$, the constant load disturbance ΔP_d=0.02 pu, and the observation interval $T = 17$ s. Let the tuning parameters $l_1 = 0$, $l_2 = 2.03$, and $H\infty$ gain $\gamma = 20$, the AoI-aware PI controller gain parameters K_p and K_I with different update periods are listed in Table 3.

Figure 4 demonstrates the performance of the one-area system with different update periods. As the update period grows from 1.4 to 2.2 s, the system performance index W decreases rapidly. While the update period

Table 2 Parameters of one-area AoI-aware LFC system

Parameter	M	D	$ß$	T_g	T_{ch}	R
Value	0.167	8.3e−3	0.24	0.08	0.30	2.40

Table 3 AoI-aware PI controller parameters of one-area

λ(s)	1.4	1.6	1.8	2.0	2.2	2.4
K_p	0.413	0.693	0.391	0.422	0.695	0.645
K_I	0.277	0.317	0.353	0.343	0.375	0.361
λ(s)	**2.6**	**2.8**	**3.0**	**3.2**	**3.4**	**3.6**
K_p	0.598	0.544	0.500	0.440	0.411	0.397
K_I	0.353	0.346	0.336	0.327	0.314	0.300
λ(s)	**3.8**	**4.0**	**4.2**	**4.4**	**4.6**	
K_p	0.381	0.367	0.353	0.341	0.327	
K_I	0.289	0.278	0.268	0.259	0.251	

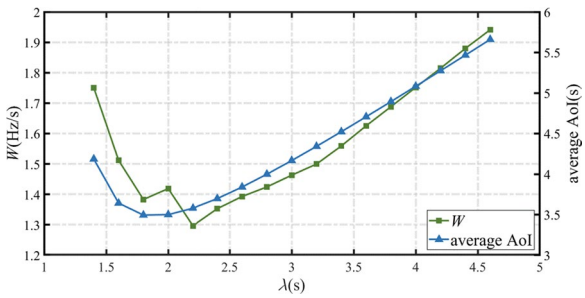

Fig. 4 Performance index W of the one-area AoI-aware LFC system with different update periods when $\Delta P_d = 0.02$ pu and the average AoI with different update periods

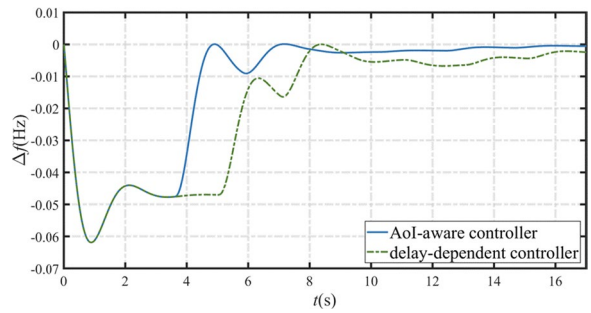

Fig. 6 Performance of the proposed AoI-aware controller and delay-dependent controller for $\Delta P_d = 0.02$ pu

increases from 2.2 to 4.6 s, the worse system frequency performance is obtained. Thus, $\lambda = 2.2$ s is the right point for optimal one-area power system performance. Figure 4 reveals that LFC performance and update period are related. Therefore, the right update period can be found directly for optimal performance. It also reveals that both too long and too short update periods significantly deteriorate the one-area power system performance.

Additionally, it can be seen from Fig. 4 that the average AoI is a convex function with the update period, while both long and short update periods lead to larger average AoI. A long update period means the control center may not receive fresh information frequently, whereas a short update period leads to information queuing in the communication channel. Figure 4 shows that the average AoI can reflect timely information updates.

Figure 5 compares the frequency deviations of the one-area power system with update periods $\lambda = 1.4$ s, 2.2 s, and 4.6 s. It is observed from Fig. 5 that the fluctuation and convergence time of Δf with $\lambda = 2.2$ s are smaller and shorter than the Δf with $\lambda = 1.4$ and 4.6 s. Thus, Fig. 5 verifies that system performance can be degraded by inappropriate update periods. For example, when $\lambda = 1.4$ s, information packets are queued heavily in the communication channel, which increases the communication delay

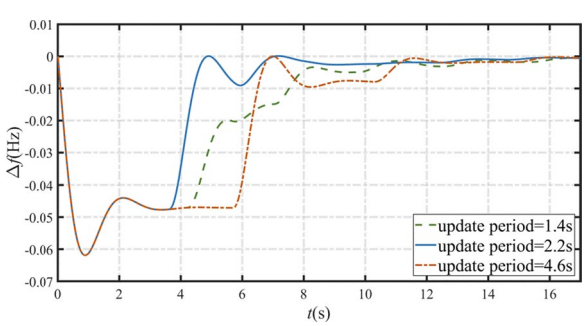

Fig. 5 Frequency deviation of the proposed one-area AoI-aware LFC under different update periods

and AoI. In contrast, when $\lambda = 4.6$ s, the control center cannot receive enough information for decisions, which leads to poor system performance. The above results are consistent with Fig. 4, which also proves the correctness of Algorithm 1 and Algorithm 2.

It is clear from Fig. 6 that the frequency deviation Δf with the proposed AoI-aware controller, excels the smaller settling time and overshoots compared to the delay-dependent controller in [9]. The superiority of the proposed controller over the delay-dependent one may attribute to AoI. Long and short update periods lead to a larger average AoI. The AoI-aware controller can improve LFC performance by choosing the optimal update period better than the delay-dependent controller. Therefore, the AoI-aware controller has better performance than the delay-dependent one.

Considering the scenario with random load disturbances depicted in Fig. 7a, it is clear from Fig. 7b that the frequency deviation Δf with the right update period of 2.2 s, excels the smallest settling time and overshoots than the others.

Figure 8 illustrates the frequency responses of the one-area system by the proposed AoI-aware controller and delay-dependent controller. It can be seen that frequency convergence during random load disturbances is quicker by the proposed AoI-aware controller than the delay-dependent controller.

Consider the one-area AoI-aware LFC system in Table 2 with GRC and GDB constraints. GRC is the constraint on the rate of change in the generating power due to physical limitations [31], while GDB is the total magnitude of a sustained speed change within which there is no change in the valve position of the turbine [32]. The nonlinear model of the GRC and GDB shown in Fig. 9 replaces the linear non-reheating steam turbine generator model in Fig. 1. The GRC of the reheat units is set as 3% of the rated power per minute [33] and the GDB is 0.036 Hz [34]. Defining the update period $\lambda = 3.0$s, the AoI-aware PI controller gains $K_p = 0.500$

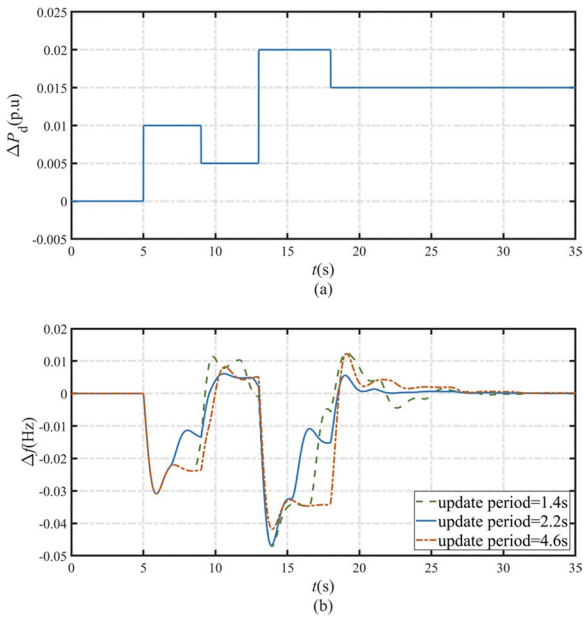

Fig. 7 Performance of the proposed one-area AoI-aware LFC under design PI controller for random load disturbances ΔP_d. **a** Random load disturbances. **b** Frequency deviation Δf

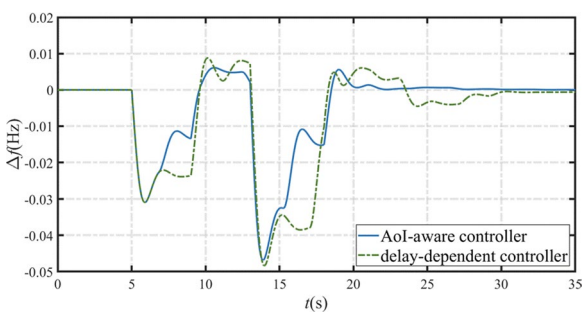

Fig. 8 Performance of the one-area system by the proposed AoI-aware controller and the delay-dependent controller with random load changes

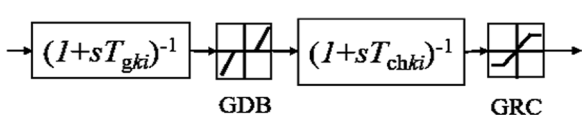

Fig. 9 Nonlinear non-reheating steam turbine generator model with GRC and GDB.

and $K_I = 0.336$, the delay-dependent controller gains [9] $K_p = 0.601$, $K_I = 0.367$ and the load disturbance $\Delta P_d = 0.02$ pu, Fig. 10 shows the frequency responses of the one-area system with GRC and GDB by the proposed AoI-aware controller and the delay-dependent controller. It is clear from Fig. 10 that frequency deviations are relatively small with the proposed AoI-aware controller.

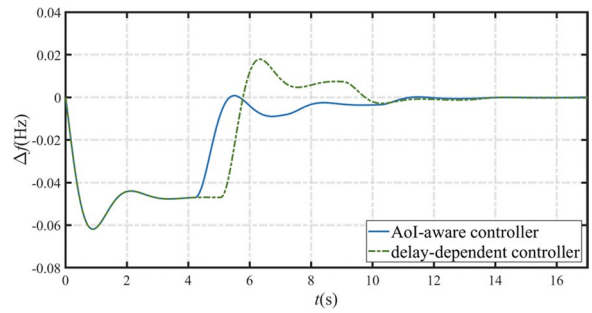

Fig. 10 Performance of the one-area system by proposed AoI-aware controller and delay-dependent controller with GRC and GDB.

It demonstrates that, when the one-area system considers the GRC and GDB, the frequency with the proposed AoI-aware controller converges faster than the delay-dependent controller.

The one-area AoI-aware LFC system in Table 2 with generator temporary faults is considered, and four identical generators are selected with rated capacity of 100 MVA, i.e., $S_{N1}=S_{N2} = S_{N3} = S_{N4} = 100$ MVA, and reference power value of 2000 MVA. Assume the load capacity is 100 MVA and the four generators distribute the power generation equally. Under normal operating conditions, each generator produces 25 MVA power output. In this case, it assumes that the first, second, and third generators have temporary faults at 3–8 s, 12–18 s, and 11–15 s, respectively. The update period is $\lambda = 2.2$ s, the AoI-aware PI controller gains are $K_p = 0.695$, $K_I = 0.375$, the delay-dependent controller gains are $K_p = 0.698$, $K_I = 0.243$, and the load disturbance $\Delta P_d = 0.02$ pu.

Figure 11a shows that the frequency deviation Δf with the proposed AoI-aware controller excels the smaller settling time and overshoots compared to the delay-dependent controller with generator temporary faults. Figure 11b, c respectively illustrate the generator mechanical power output deviation under generator temporary faults with the AoI-aware controller and delay-dependent controller. It is clear that the generator mechanical power output deviations with the AoI-aware controller are relatively small.

4.3 Two-area AoI-aware LFC

Considering a two-area AoI-aware LFC system, the system's parameters are reported in Table 4. It assumes that $\alpha_1 = \alpha_2 = 1$, the constant load disturbance $\Delta P_d = 0.02$ pu, the observation interval $T = 27$ s, and $l_1 = 0$, $l_2 = 2.03$, $\gamma = 20$. Different AoI-aware PI controller gain parameters K_{p1}, $K_{I1,}$ and K_{p2}, K_{I2} are calculated by following Algorithm 2 as shown in Tables 5 and 6, respectively. K_{p1}, $K_{I1,}$ and K_{p2}, K_{I2} represent the AoI-aware controller gains for area 1 and area 2, respectively. the AoI-aware LFC system

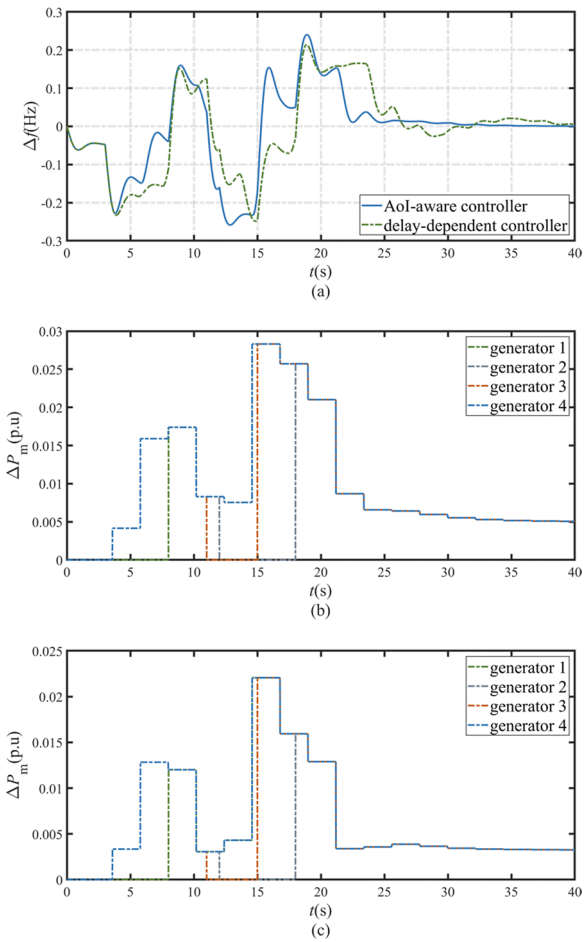

Fig. 11 Performance and generator mechanical power output of the one-area system by proposed AoI-aware controller and delay-dependent controller with generator temporary faults: **a** Frequency deviation Δf; **b** Generator mechanical power output with an AoI-aware controller; **c** Generator mechanical power output deviation with a delay-dependent controller

performance W is then calculated by Algorithm 1 as shown in Fig. 12.

Figure 12 shows the performance index W with different update periods. It shows that system performance is improved as the update period grows from 1.4 to 2.2 s. When the update period increases from 2.2 to 4.6 s, the system frequency performance degrades. Therefore, the update period 2.2 s is the right choice for the system. A long or short update period makes the system performance index W worse. The results are similar to those in Fig. 4.

To show the superiority of the right update period on improving the system performance, Fig. 13 compares the performances with different update periods and same load disturbance in the two-area system. It can be seen from Fig. 13a that when area 1 has the right update period of 2.2 s, the frequency converges faster with less fluctuation. For area 2, similar results can be seen from Fig. 13b. The above results are consistent with Fig. 12, proving the correctness of Algorithm 1 and Algorithm 2.

Figure 14 illustrates the superiority of the AoI-aware controller to stabilize the two-area power system with load disturbance. It can be seen from Fig. 14a that the AoI-aware PI controller stabilizes the frequency of area 1 in 15 s. However, the delay-dependent controller stabilizes the system in around 25 s. A similar conclusion can be seen for area 2 from Fig. 14b. $\lambda = 2.2$ s is the right update period for the two-area system. The AoI-aware controller can improve LFC performance through choosing the right update period but the delay-dependent controller is unable to. Therefore, the AoI-aware controller has better performance than the delay-dependent one.

Considering the scenario with random load disturbances of area 1 and area 2, the results are depicted in Fig. 15a, b, respectively. Additionally, it can be seen from Fig. 15c that the AoI-aware PI controller in area 1 with the optimal update period of 2.2 s results in faster convergence and less fluctuation in the frequency. Figure 15c shows that with the random load disturbance, the performance of the area 1 system can be improved by using the right update period. A similar conclusion for area 2 can be seen from Fig. 15d.

Figure 16 shows the abilities of the proposed AoI-aware controller and delay-dependent controller to stabilize the two-area power system. It has random load disturbances shown in Fig. 15a. It can be seen from Fig. 16a that frequency convergence is quicker by using the proposed AoI-aware controller for area (1) Additionally, Fig. 16b demonstrates that AoI-aware LFC response is faster in area (2) Above all, the AoI-aware controller shows superiority in stabilizing the power system than the delay-dependent controller.

Table 4 Parameters of the two-area AoI-aware LFC system

Parameter	M	D	$ß$	T_g	T_{ch}	R
Area 1	0.20	0.010	0.51	0.08	0.30	2.00
Area 2	0.24	0.015	0.51	0.15	0.30	2.00
$T_{12} = 0.0796$ pu/rad						

Table 5 AoI-aware PI controller parameters of area 1

λ(s)	**1.4**	**1.6**	**1.8**	**2.0**	**2.2**	**2.4**
K_{p1}	0.381	0.520	0.352	0.316	0.610	0.671
K_{I1}	0.170	0.216	0.241	0.248	0.242	0.233
λ(s)	**2.6**	**2.8**	**3.0**	**3.2**	**3.4**	**3.6**
K_{p1}	0.566	0.512	0.496	0.485	0.480	0.475
K_{I1}	0.226	0.218	0.209	0.201	0.194	0.187
λ(s)	**3.8**	**4.0**	**4.2**	**4.4**	**4.6**	
K_{p1}	0.465	0.454	0.441	0.429	0.415	
K_{I1}	0.183	0.176	0.170	0.162	0.156	

Table 6 AoI-aware PI controller parameters of area 2

λ(s)	**1.4**	**1.6**	**1.8**	**2.0**	**2.2**	**2.4**
K_{p2}	0.388	0.486	0.329	0.363	0.773	0.589
K_{I2}	0.174	0.222	0.247	0.250	0.245	0.240
λ(s)	**2.6**	**2.8**	**3.0**	**3.2**	**3.4**	**3.6**
K_{p2}	0.522	0.499	0.492	0.490	0.484	0.474
K_{I2}	0.233	0.225	0.217	0.211	0.206	0.196
λ(s)	**3.8**	**4.0**	**4.2**	**4.4**	**4.6**	
K_{p2}	0.458	0.441	0.425	0.411	0.397	
K_{I2}	0.189	0.181	0.174	0.166	0.160	

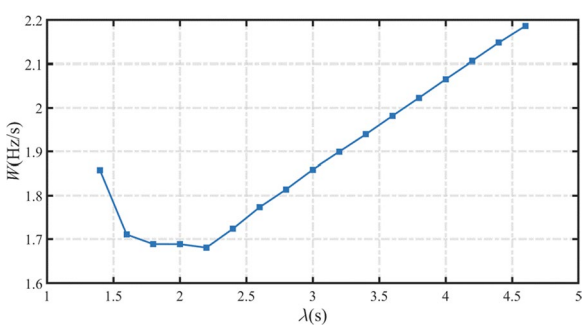

Fig. 12 Performance index *W* of the two-area AoI-aware LFC system under different update periods when ΔP_d = 0.02 pu

The two-area AoI-aware LFC system in Table 4 with GRC and GDB constraints is now considered. Set the GRC of the reheat units as 3% of the rated power per minute [33] and the GDB as 0.036 Hz [34]. Define the update period $\lambda_1 = \lambda_2 = 3.0$ s, the area 1 AoI-aware PI controller gains K_{p1} = 0.496, K_{I1} = 0.209, the delay-dependent controller gains K_{p1} = 0.542, K_{I1} = 0.251, the area 2 AoI-aware PI controller gains K_{p2} = 0.492, K_{I2} = 0.217, the delay-dependent controller gains K_{p2}

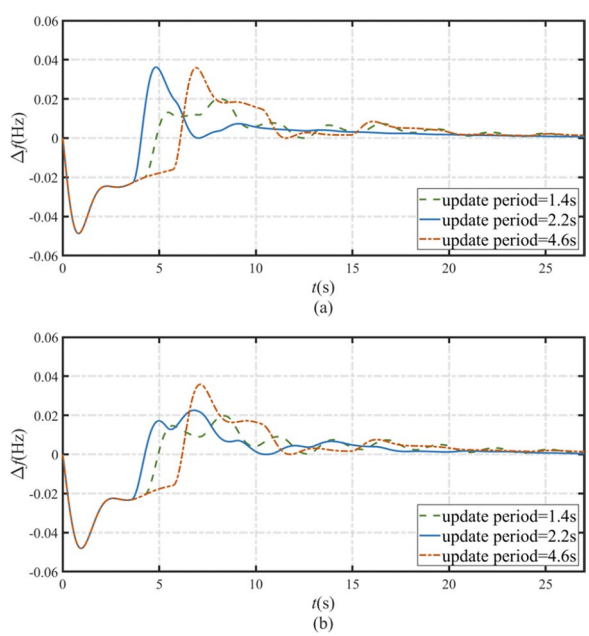

Fig. 13 Performance of the proposed two-area AoI-aware LFC under different update periods for ΔP_d=0.02 pu: **a** Area 1 frequency deviation; **b** Area 2 frequency deviation

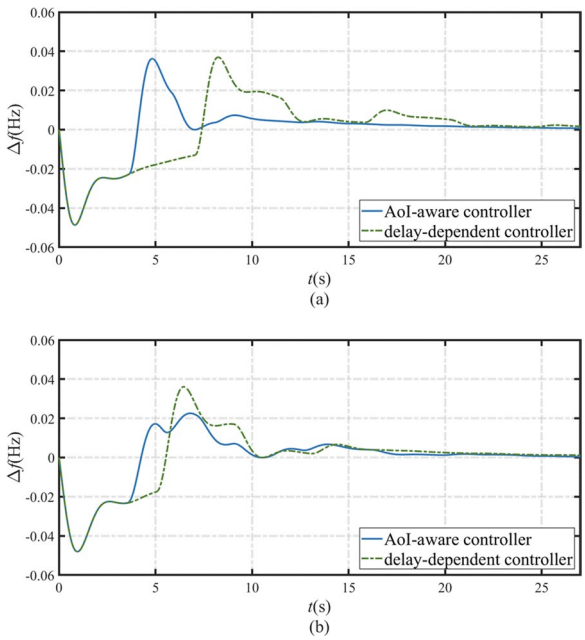

Fig. 14 Performance of the two-area system by proposed AoI-aware controller and delay-dependent controller in [9] for $\Delta P_d = 0.02$ pu: **a** Area 1; **b** Area 2

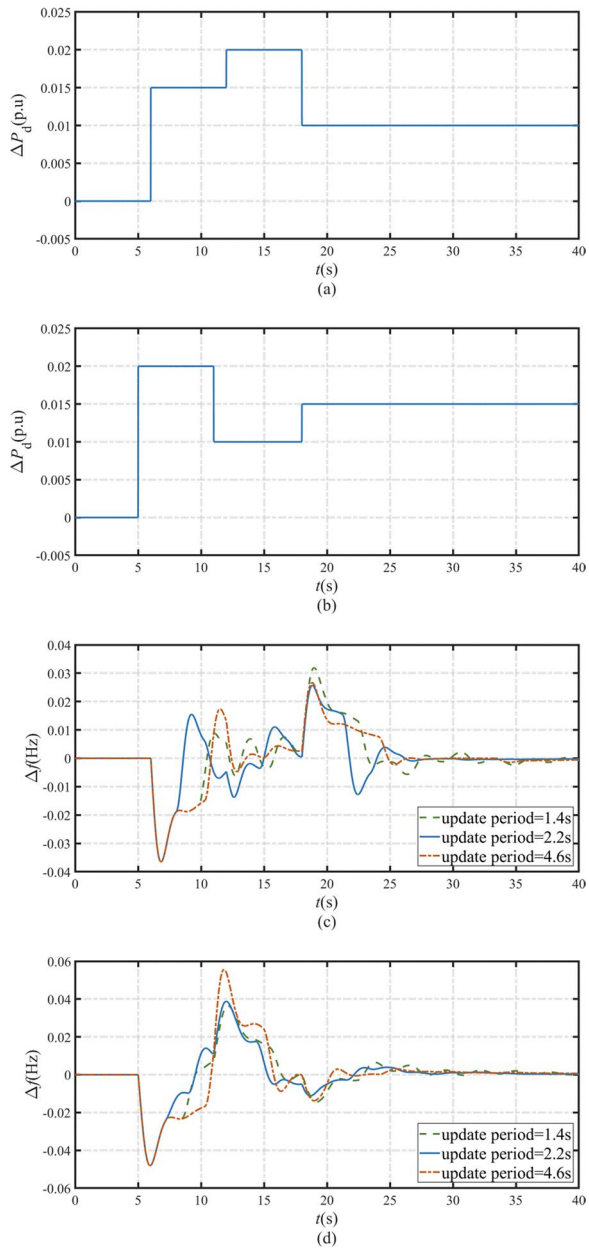

Fig. 15 Performance of the proposed two-area AoI-aware LFC under different update periods for random load disturbance: **a** Random load disturbance of area 1; **b** Random load disturbance of area 2; **c** Area 1 frequency deviation; (d) Area 2 frequency deviation Δf

$= 0.540$, $K_{I2} = 0.253$ and the load disturbance $\Delta P_d = 0.02$ pu. Figure 17 shows the superiority of the proposed AoI-aware controller compared with the delay-dependent controller in stabilizing the two-area power system with GRC and GDB. It can be seen from Fig. 17a that frequency convergence is quicker by using the proposed AoI-aware controller for area 1, while Fig. 17b demonstrates that LFC with an AoI-aware controller response is also faster in area 2.

The two-area AoI-aware LFC system in Table 4 with generator temporary faults is considered. Each area elects four identical generators with a rated capacity of 100 MVA, and the reference power value of this two-area system is 2000 MVA. Assume the load capacity is 100 MVA and the four generators in each area distribute the power generation equally. In area 1, the first, second, and third generators have temporary faults at 10–15 s, 7–16 s, and 9–13 s, respectively. Additionally, with the update period $\lambda = 2.2$ s, the AoI-aware PI controller gains $K_{p1} = 0.610$, $K_{I1} = 0.242$, the delay-dependent controller gains $K_{p1} = 0.502$, $K_{I1} = 0.136$, and the load disturbance $\Delta P_d = 0.02$ pu, Fig. 18a shows area 1 frequency deviations with the proposed AoI-aware controller and the delay-dependent controller under generator temporary faults. Figure 18b, c respectively illustrate area 1 generator mechanical power output deviations under generator temporary faults with the AoI-aware controller and the delay-dependent controller. As seen, Fig. 18 clearly illustrates the superiority of the AoI-aware controller in stabilizing the area 1 system with generator temporary faults.

In area 2, the first and third generators have temporary faults at 5–16 s and 17–23 s, respectively. The update period is $\lambda = 2.2$ s, the AoI-aware PI controller gains are $K_{p2} = 0.773$, K_{I2}=0.245, the delay-dependent controller gains are $K_{p2} = 0.440$, $K_{I2} = 0.181$, and the load

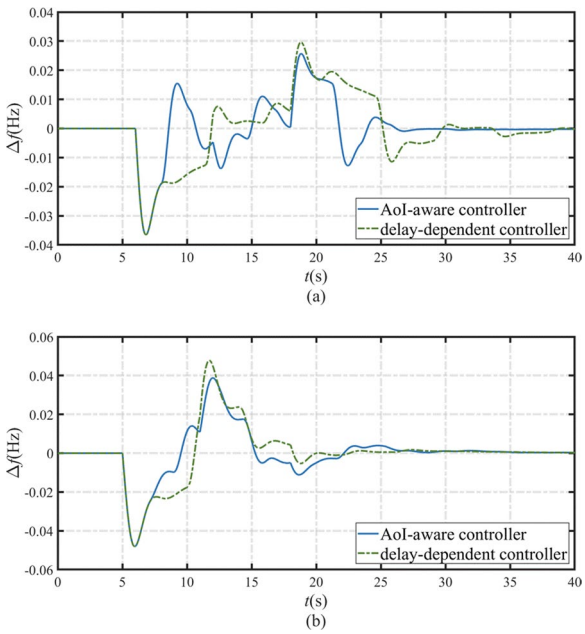

Fig. 16 Performance of the two-area system by proposed AoI-aware controller and delay-dependent controller for random load disturbance: **a** Area 1; **b** Area 2

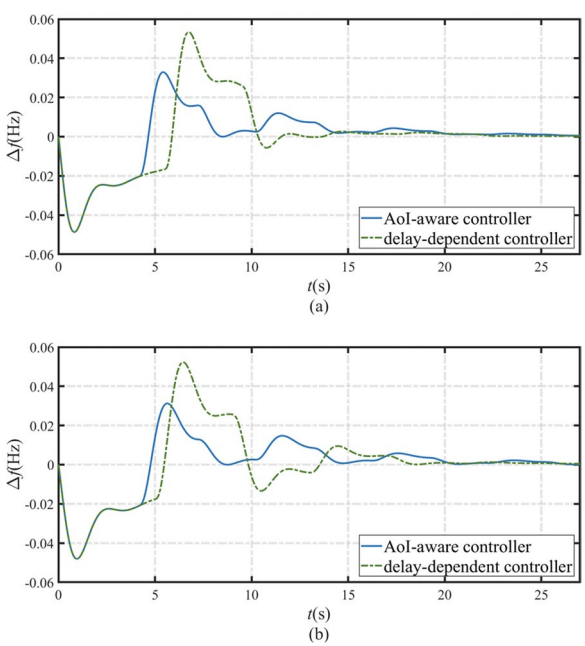

Fig. 17 Performance of the proposed two-area AoI-aware LFC under different update periods for random load disturbance: **a** Area 1 frequency deviation; **b** Area 2 frequency deviation

disturbance is $\Delta P_{\mathrm{d}} = 0.02$ pu. Figure 19 illustrates the superiority of the proposed AoI-aware controller compared with the delay-dependent controller in stabilizing

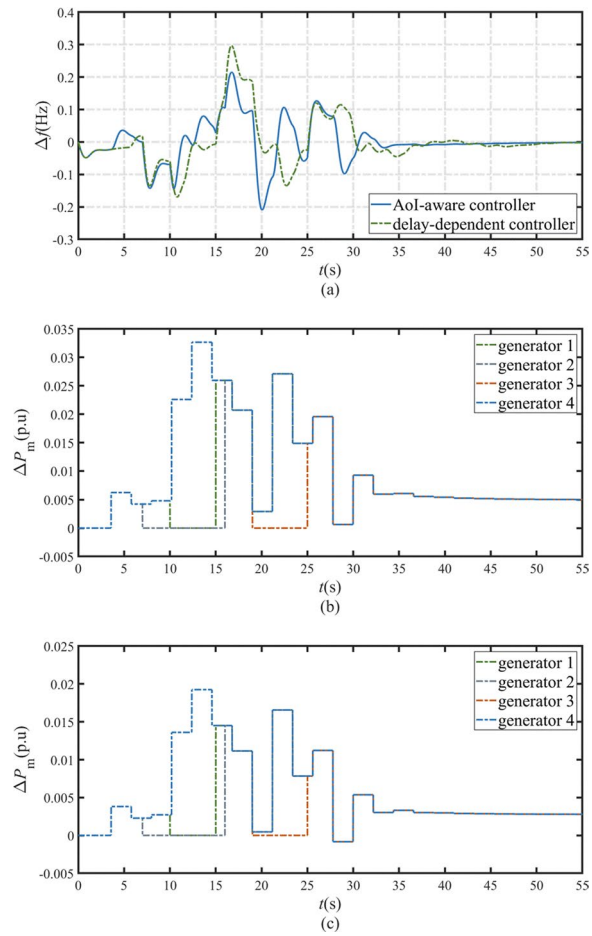

Fig. 18 Area 1 performance and generator mechanical power output of the one-area system by proposed AoI-aware controller and delay-dependent controller with generator temporary faults: **a** Frequency deviation; **b** Generator mechanical power output with an AoI-aware controller; **c** Generator mechanical power output deviation with a delay-dependent controller

the area 2 system. The area 2 generator mechanical power output deviations under generator temporary faults with an AoI-aware controller and a delay-dependent controller are respectively shown in Fig. 19b, c. It can be seen from Fig. 19a that frequency convergence is quicker by using the proposed AoI-aware controller for area 2.

5 Conclusion

This paper designs an AoI-aware PI-type controller to optimize LFC performance. AoI is first applied to characterize information staleness, and in comparison with communication delay, AoI contains control factors of the update process and provides the communication system model controllability. Compared with the delay-dependent controller, the AoI-aware controller greatly improves the LFC system performance. Different AoI-aware PI-type controllers are then designed for different update

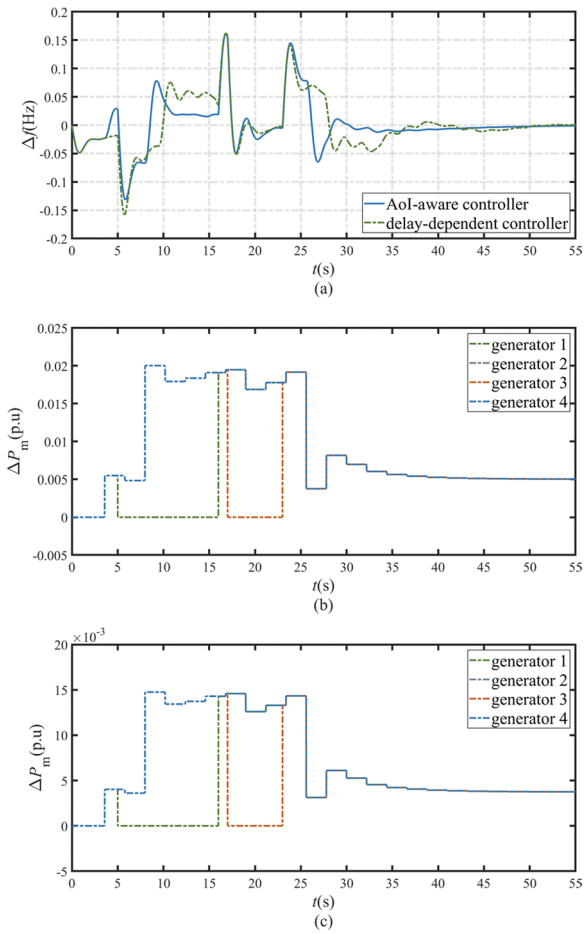

Fig. 19 Area 2's performance and generator mechanical power output of the one-area system by the proposed AoI-aware controller and the delay-dependent controller with generator temporary faults. **a** Frequency deviation **b** Generator mechanical power output with an AoI-aware controller **c** Generator mechanical power output deviation with a delay-dependent controller

periods according to EDR based on the AoI-aware LFC model. A right AoI-aware PI-type controller and update period are selected according to the degree of frequency fluctuation of the power system. The case studies show the effectiveness of the proposed AoI-aware PI-type controller. When the LFC system has the right AoI-aware PI-type controller and update period, high performance can be achieved. It also illustrates the superiority of the proposed AoI-aware controller over the delay-dependent controller in stabilizing the LFC system. In the future, redesigning a controller based on the AoI-aware LFC model with the GRC and the GDB may be considered by chaos-based firefly algorithm or firefly algorithm.

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Authors contribution
Conceptualization: DJ, XZJ and CRL. Methodology: DJ and CRL. Validation: DJ and CRL. Formal analysis: DJ, CRL, and CZS. Writing—original draft: DJ. Writing—review and editing: DJ, CRL, and CZS. Supervision: KGX and BH. All the authors read and approved the final manuscript.

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Availability of data and materials
Data and materials are obtained simulation program. This simulation program is MATLAB.

Declarations

Competing interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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