AGE-OF-INFORMATION-AWARE LOAD FREQUENCY CONTROL AND STABILITY ANALYSIS

by

Dan Jiao

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ABSTRACT

STABILITY ANALYSIS OF LOAD FREQUENCY CONTROL BASED ON AGE-OF-INFORMATION

by

Dan Jiao

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Under the Supervision of Dr. Yi Hu

Nowadays, modern load frequency control (LFC) systems employ an open communication system, which causes information staleness inevitably to arise. This issue can degrade the regulation performance of LFC and even threaten stability. This thesis introduces age-of-information (AoI) into LFC to describe the information freshness at the control center. Unlike communication delay, AoI can provide real-time information state based on information update rate. In this thesis, a muti-area LFC-AoI model is built to evaluate the update rate effect on LFC performance. Then, an AoI-based stability criterion for discrete LFC systems is built. After that, the AoI margin is proposed and compared with the communication delay margin. Next, an algorithm is introduced to design a PI-type controller based on a specific update rate for a one-area power system. Then, fluctuation of LFC frequency as a performance metric guides the power system to choose the right update rate.

Case studies are carried out based on the one-area power system. Simulation results show the necessity of considering the update rate effect on LFC performance, the AoI margin is larger than the delay margin and the large extent depends on the update rate. And the performance of LFC can be optimized under the right update rate

and designed PI-type controller.

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NOMENCLATURE

Parameters

λ	Update rate
μ	Service rate
ρ	Server utilization
g_k	Age-of-information of information *k* at the information receiver
S_k	Service time of information *k*
X_k	Update interarrival time of information *k*
M	Generator moment of inertia
D	Damping coefficient
T_g	Update rate governor time constant
R	Update rate speed drop coefficient
K_l	Update rate integral gain
K_p	Update rate proportional gain
θ	frequency deviation factor of area *i*

Variables

$x(t)$	State vector
$u(t)$	Output of the controller
Δf_i	Frequency deviation of area *i*
ΔP_{vi}	Control valve position deviation of area *i*
ΔP_{di}	Load deviation of area *i*
ΔP_{mi}	Generator mechanical power output deviation of area *i*
ΔP_{tiei}	Net exchanged power deviation on the area *i* contact line
ACE_i	Area control error (ACE) of the *i*-th control area

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Chapter 1 Introduction

1.1 Background

Cyber-Physical System (CPS) is a very complex system because it includes the computer, network, and physical environment [1-4]. At first, a scientist who reached on embedded systems mentioned the concept of CPS. Then in recent years, this concept has aroused many fields' attention.

Cyber-physical interconnected systems achieve profound integration of computing resources with the physical world. In the power system, the application of embedded devices, the model chosen in cyber-physical systems, the timing setting, as well as the communication structure including huge information and information integration, are the key technologies to build the specific power systems. These power systems can connect information systems and physical systems. In addition, the continuous process and discrete process are cooperated in these power systems [1].

With the development of communication technology and new energy, communication networks are becoming more and more complex and new energy is being used more and more widely, so the stability of the communication system is very important for the stability of the power system. On the one hand, the cyber-physical power system represents the deep integration of the power system and communication system, and as the new energy is widely connected to the power system. The service area, the number of sensors, and the number of control centers of the CPS will increase massively.

Load frequency control (LFC) is a typical class of cyber-physical power system applications and one of the most significant aspects of the power system operation and control process [17]– [18]. It uses open communication systems to regulate the huge amount of demand response resources and conventional unit output [5], [6], thus maintaining the frequency stability of the power system and the power balance between the contact lines. Open communication systems are the preferred choice for LFC systems due to their low cost and flexibility compared to traditional dedicated communication channels [7]. Additionally, with the increasing decentralization of service recipients, modern power systems are highly in need of an open communication infrastructure [3], and this trend will be enhanced by the current development of smart grid technologies, in which communication systems support the integration of information technology and power systems.

However, open communication systems introduce some new risks into LFC systems, such as communication delay [8], [9]. Unlike traditional power systems, a huge number of demand response resource regulation commands flood into the communication system at the same moment, causing congestion in the channel, which in turn triggers communication delay. Studies have shown that communication delays will reduce the ability to quickly restore frequency stability and may even induce frequency instability in power systems. Therefore, it is necessary to consider the analysis and control of LFC systems considering communication delay.

The previous research only employs information packet-centric performance metrics communication delay to describe the information packet freshness. For instance, the simulation results in [20] illustrated that the communication delay in LFC systems can vary in the interval [0.15, 2] seconds when an open communication system is considered. As research progresses, the communication delay model in LFC systems becomes more complex and the simulations more accurate. Communication delay is a physical quantity that describes the transmission time of each packet and portrays the degree of staleness of each packet. But in CPS systems, we need to analyze the impact of the received information on the physical system from the perspective of the information receiving end. However, the packet-centric communication delay alone cannot accurately portray the freshness of the packet for the data receiving end because it cannot fully capture the freshness of the packet. For example, despite the short packet communication, the controller still receives stale information because it does not receive new packets frequently. In another word, the communication delay cannot describe the whole information update process. The update process describes the process that which the information is firstly updated by the sensor, then transmitted through the channel, and finally received by the controller.

Modern LFC has considerably increased the need for real-time information updates. A new performance metric, called Age of information (AoI), was proposed in [13], [14] to describe the information freshness at the information receiver, like the control center of the power system. The AoI portrays the time elapsed from the moment the freshest packet is received by the information receiver from the moment it is generated. Whenever a new packet is received by the control center, the AoI decreases to the time elapsed from the generation of that packet to the application of this packet by the control center, while in other cases the AoI increases linearly.

AoI considers the whole update process, so it can ensure the information freshness, is as timely as possible at the control center by using the right update rate. The right update rate is neither updating information as fast as possible nor ensuring that the information packet is received with minimum communication delay. To some extent, the sensors should maximize the utilization of the communication channels. However, delivering an information packet to the controller requires a nonzero and random time, which depends on the communication channel and previous queued packets.

Next, we will discuss the difference between AoI and communication delay. Although both communication delay and AoI are metrics that portray the degree of aging, they are described by different objects. Communication delay is a packet-centric metric that portrays the aging degree of each packet, while AoI is a packet-centric metric that portrays the freshness of the packet for the information receiver. Therefore, the AoI not only studies the transmission process of packets but also focuses on the packet turnover project at the information receiving end and captures the information degree of packets for the information receiving end completely. Therefore, the turnover frequency of packets affects their freshness for the information receiving end. For example, while low update frequency leads to short queuing delays, the control center may end up with stale data due to infrequent updates. On the other hand, a high update frequency can cause packets to become stale over a long queue. And the delay only considers the transmission quality of each packet, so it only considers the long packet queuing delay due to high update frequency and ignores the potential instability caused by the physical system of packets with low update frequency. In addition, packet transmission is considered an exogenous process that cannot be controlled, so the delay is uncontrollable. Whereas the AoI will vary with the update frequency is controllable.

The performance of the information freshness system can be significantly affected by the update rate [23]– [25]. A high update rate causes a lack of information at the power system control center. A low update rate results in information packet congestion occurring in the communication channel. The above two cases result in the control center receiving information not freshness, which then influent the performance of LFC. In the existing perception of power systems, the information update process is considered an exogenous process that cannot be controlled.

On the other hand, LFC systems have higher requirements for optimizing packet freshness under open communication systems. To improve the LFC performance, recently, advanced control methods, like sliding mode control [16, 17], active disturbance rejection control [18], model-based control [19], and model predictive control [20] are introduced. However, most of these advanced methods suggest complex state feedback or high-order dynamic controllers. [21] shows that the PID-type controller is still preferred by power systems. These advanced control methods do not consider the effects of the whole update process at the design stage of a controller. The above controllers are based on communication delay. However, packet-centric communication delay does not fully capture the freshness of packets. On the contrary, AoI, a system-centric metric, describes the complete process from "generation" to "discard" of packets to the control center, so it can accurately portray the freshness of packets to the system. Therefore, for the LFC system, a PI-type controller is designed based on AoI, which can meet the requirements of the LFC system to optimize the performance in an open communication system

Additionally, a suitable update rate can optimize the LFC performance. As mentioned above, in traditional communication systems where communication delay is an indicator, packet arrival at the control center is considered an exogenous process that cannot be controlled, so these packets can be generated randomly. However, in reality, updating packets at the right rate will allow the LFC system control center to receive fresher packets. Adjusting the packet update frequency allows the control center to accept fresh packets to make accurate and reasonable decisions, thus making the LFC system performance more stable, which is essential for the stable and safe operation of the power system.

Above all, this paper chooses a suitable update rate and designs a PI-type controller based on AoI to joint optimize the LFC performance. This achieves the goal of controlling the physical side from the information side, thus achieving the purpose of joint optimization of the information side and the physical side. The physical information system is a whole, if only optimizing the information side or the physical side can only get the local optimal solution, but the locally optimal solution is not always the global optimal solution, so the layout optimization results do not have accuracy. The LFC system performance is optimized by controlling the update frequency of packets, which realizes the coupling of the information side and physical side, and when the physical side of the LFC system changes, the update frequency of the information side will be adjusted accordingly. Therefore, such a joint optimization model of update frequency-LFC system performance can yield a global optimal solution and is very inclusive of changes in system internal conditions. With the use of open communication systems in LFC systems, it is of great significance to optimize the LFC system performance by adjusting the update rate of information from the information side and design a PI-type controller from the physical side which are important for the stability of the LFC system.

1.2 Problem Description

Compared with traditional communication channels, open communication systems have become the first choice for modern LFC systems because of the advantages of low cost and high flexibility, but also put forward higher requirements for the optimization of information freshness to keep LFC stability, the traditional communication system delay indicators can no longer meet, so we introduce AoI to characterize the freshness of packets in the control center to provide a theoretical basis for the subsequent optimization of packet freshness. The control center receives the packets that are not fresh and may make decisions that are far from the actual situation, thus affecting the stability of the LFC system. Therefore, the update rate plays a significant role in the stability of the LFC system. It is very significant for the stable and economic operation of the power system. The key issues that need to be addressed are as follows

(1) Compare the concepts of AoI and communication delay, explain the superiority

of AoI, and introduce AoI into LFC systems.

(2) Understand the reasons for the staleness of the AoI and study the effect of information packet update frequency on the average AoI.

(3) Construct stability criterion of load frequency control system depends on the AoI.

(4) Compare the difference between the AoI domain and the communication delay domain.

(5) Design algorithms to design the PI-type controller and find the update frequency that can make the system performance optimal.

1.3 Contribution

(1) The concept of the AoI is introduced into the LFC control system to portray the freshness of information packets for the control system, which provides a basis for the LFC control system to optimize information freshness in open communication systems.

(2) A multi-area LFC-AoI model is constructed to show the information freshness and update rate effect on LFC performance.

(3) Constructed the stability criterion of the LFC system that depends on the AoI.

(4) The AoI domain is compared with the delay domain and the superiority of the AoI domain is introduced.

(5) The algorithm is constructed to design the PI-type controller and use the update frequency that can make the LFC system perform optimally.

1.4 Thesis Structure

Chapter 2 AoI is introduced to portray the information freshness for the control center. Additionally, the communication system structure is introduced. Next, the multi-area LFC-AoI system is built. Then, an AoI-based stability criterion for discrete LFC systems is built.

Chapter 3 Based on the LFC-AoI system model proposed in chapter 2. This chapter shows that the AoI margin is different from the delay margin. AoI margin depends on the information freshness and the update rate of the communication system. The delay margin is determined by the information packet staleness. Therefore, for a single-area LFC system, the AoI margin is a two-dimensional space while the delay domain is a one-dimensional space. The calculation of the AoI margin is very challenging because it should consider the update rate. To illustrate the impact of update rate on AoI margin, this chapter is based on the structure of the communication system and the communication queue model in chapter 2.

Chapter 4 This chapter proposes an algorithm to design PI controllers based on AoI. This algorithm is different from the communication delay-based PI controller design, where the update rate decides the information freshness in the update process. Next, the fluctuation of LFC frequency is introduced as a performance metric to guide choosing the right update rate for a power system. One-area systems have been undertaken to demonstrate show the necessity of considering the update rate effect on LFC performance, and the performance of LFC can be significantly optimized by the right update rate and design PI-type controller.

Chapter 2 Stability Analysis of Load Frequency Control Based on Age-of-Information

From a stability analysis point of view, it is very important to find the impact of information freshness for information receivers on the frequency deviation of the LFC system. The case discusses the maximum AoI that allows the LFC system's frequency to remain stable. Here, we assume inputting a small constant external disturbance.

The contributions of this chapter are 1) Introducing AoI into the LFC stability analysis study; 2) Building an LFC-AoI model. 3) Propose an AoI-dependent stability criterion for a single-area LFC system.

2.1 Communication System

2.1.1 Structure of Communication System

The power system cannot keep stable without a reliable communication system. Here, we stand in the perspective of the power system to introduce a structure of the communication system. The communication system includes many devices such as sensors and controllers which are connected by information channels. The sensors update information required by the LFC system such as frequency deviation, generator mechanical power output deviation, etc. Then the information is queued when it waits to be transmitted by the communication channel. Next, the information is transmitted through the communication channel before it is received by controllers. The whole process is called the information update process.

A "generate-at-will" model was proposed in [12], which is shown in **Figure 2.1**. Through acknowledgments (ACKs), the source node such as sensors can know the channel’s idle or busy state. Therefore, the source node can generate information at any time of its own will. Information reaches the destination node such as the control center through the channel.

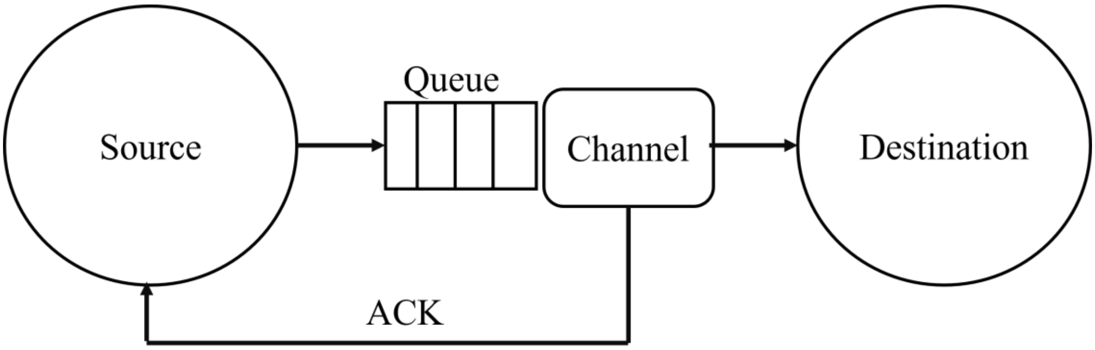

Figure 2.1 Communication system model

The “generate-at-will” communication system is different from the traditional communication system in two parts. Firstly, the traditional communication systems consider information arriving at the controller as an exogenous and unpredictable process. However, the sensors can update the information of their will.

Therefore, information arrival can be controlled. Updating information at the right rate can deliver more fresh information to the controller [13]. A high update rate leads to information queuing in front of the communication channel. On the other hand, a low update rate results in the controller infrequently receiving information.

Secondly, traditional communication systems consider information packet-centric performance metrics like delay. However, these performance metrics cannot fully capture the information freshness. If the control center can regularly receive fresh information through the right update rate, the delay of the information packet, which is caused by information queuing, does not need to be considered.

Suppose the information passed to the sensors is queued first-come-first-served (FCFS) for transmission to the controller. Communication channels decide the transmission time of information. The transmission time includes or does not include the retransmission and backoff. The communication channel results in retransmission and other transmission activities result in backoff. Even though communication system which considers these effects becomes intricate and complex,

This thesis considers the standard M/M/1 queue model for FCFS disciples, as shown in **Figure 2.2**. The FCFS M/M/1 communication system has an update rate λ and service rate μ. Information is updated at the sensor as a rate λ Poisson distribution and is received at the controller as a rate μ Poisson distribution. $\rho=\lambda/\mu$ is introduced as server utilization which presents the ability of a communication system to process information. For a communication system, a low server utilization results in the controller receiving infrequent updates. On contrary, high server utilization means the communication channel is always in a busy state which easily causes channel congestion.

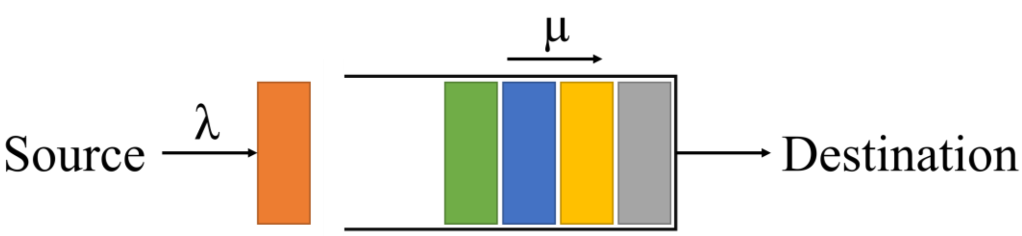

Figure 2.2 Communication system queueing model

The source node generates information at λ rate, called update rate and the destination node receives information at μ rate, called service rate. Hence, the ability of a communication system to process information can be expressed λ/μ, called offered load. For a communication system, a low offered load means the destination node receives infrequent updates. high offered load means the channel is always in a busy state which easily causes channel congestion. In this thesis, we consider the first come first served (FCFS) service principle and M/M/1 system. M/M/1 system means both the update rate λ and service rate μ are distributed according to Poisson.

2.1.2 Definition of AoI and Average AoI

In a modern communication system, a new performance measure metric, called Age of information (AoI), was proposed in [13], [14] to measure information freshness at the destination node. In this thesis, the controller represents the destination node. AoI at the controller at the time *t*, is the time since the last received information was updated at then sensor. Therefore, at any time *t*, when the freshness information *k* received at the controller was updated at time t_k, the AoI $g_k(t)$ at the controller can be defined as [15],[16].

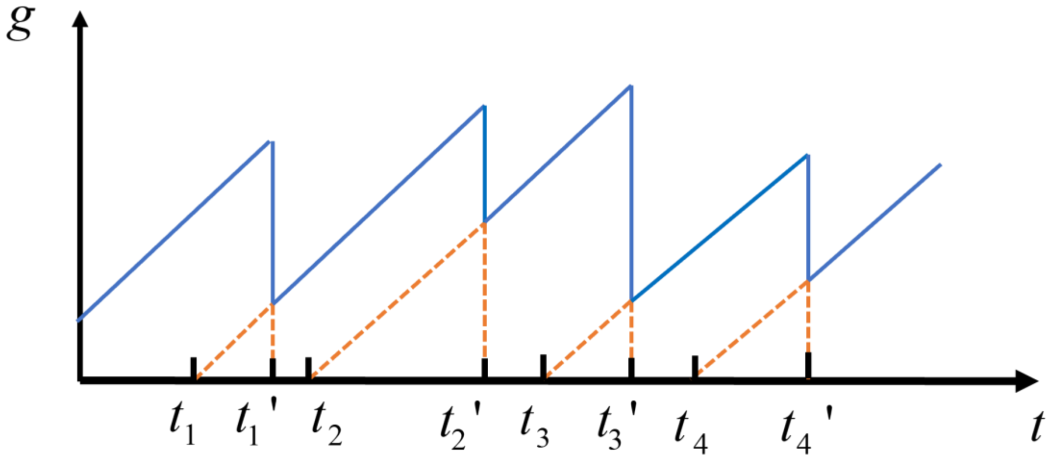

Figure 2.3 Evolution of the AoI $g_k(t)$

$$g_k(t) = t - \max\{t_k \,|\, t_k' < t\} \tag{2.1}$$

AoI is the time elapsed from the moment when the freshest information is generated. It describes the information freshness of the information receiver. The AoI $g_k(t)$ is a stochastic process that whenever a new information packet is received by the control center, the AoI grows from the communication delay of that information until the next information is received by the control center. As shown in **Figure 2.3,** When the control center receives the information k at t_k', the AoI drops to the information k's communication delay and then continues to linear grow until the information k+1 is received at t_{k+1}'.

To investigate the nature of AoI in the process of smooth information update, the average AoI of a communication system is defined as:

$$E\left[g_k\right]=\lim_{T\to\infty}\frac{1}{T}\int_0^T g_k(t)dt \tag{2.2}$$

For simplicity of exposition, the length of the observation interval is chosen to be $T\to\infty$. The numerator in (2.2) represents the area enclosed by $g_k(t)$ and the t-axis at $0<t<T$. Different information update principles will have different average AoI of a communication system.

The update rate affects how fresh the information is to the information receiver because while a high update rate leads to short queuing delays, the control center may end up with stale information due to infrequent updates. On the other hand, a low update rate can cause the information to become stale during long queues. Next, the relationship between the update rate and AoI will be presented.

Different information update processes will have different average AoI at the information receiver [16]. Here, the first come first served (FCFS) M/M/1 system is used. In addition, the information k is submitted at t_k and then delivered at t_k', and its service time is S_k; the update interarrival time is X_k.

$$S_k = t_k' - t_k \tag{2.3}$$

$$X_k = t_k - t_{k-1} \tag{2.4}$$

Under the M/M/1 system, both S_k and X_k are independent identically distributed (IID) random variables and obey Poisson distribution. In this thesis, we consider the first come first served (FCFS) service principle and M/M/1 system. At this point, the average AoI of the FCFS M/M/1communication system is [13].

$$g = \frac{1}{\mu}\left(1 + \frac{\mu}{\lambda} + \frac{\lambda^2}{\mu^2 - \mu\lambda}\right) \tag{2.5}$$

$$\mu = \frac{1}{E[S_k]} \tag{2.6}$$

$$\lambda = \frac{1}{E[X_k]} \tag{2.7}$$

Here, represents the average AoI under the M/M/1 queue. λ is known as the update rate; μ is known as the service rate. When the information system's service rate μ is fixed, its average AoI is a convex function of the update rate λ. Therefore, when the update rate λ.is too high or too low, it will lead to the information is not fresh. If the update rate λ is too high or too low, it will lead to the information is not fresh. For example, when $\lambda \to 0$, information tends to become stale during long queues. When $\lambda \to \infty$, the control center may receive stale information due to infrequent updates.

2.2 LFC-AoI System

In this chapter, a dynamical model of LFC-AoI system for the power system is constructed, which reflects the impact of the update rate of the information for the information receiver on LFC system performance. Considering the impact of AoI, obtain a multi-area LFC system with AoI.

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) + F\Delta P_{\mathrm{d}} \\ y(t) = Cx(t) \end{cases} \tag{2.8}$$

$$x(t) = \left[x_1(t) \; x_2(t) \; \cdots \; x_{\mathrm{n}}(t) \right]^T \tag{2.9}$$

$$y(t) = \left[y_1(t) \; y_2(t) \; \cdots \; y_{\mathrm{n}}(t) \right]^T \tag{2.10}$$

$$x_{\mathrm{i}}(t) = \left[\Delta f_{\mathrm{i}} \; \Delta P_{\mathrm{mi}} \; \Delta P_{\mathrm{vi}} \; \int ACE_{\mathrm{i}} \; \Delta P_{\mathrm{tiei}} \right]^T \tag{2.11}$$

$$y_{\mathrm{i}}(t) = \left[ACE_{\mathrm{i}} \; \int ACE_{\mathrm{i}} \right]^T \tag{2.12}$$

$$u(t) = \left[u_1(t) \; u_2(t) \; \cdots \; u_{\mathrm{n}}(t) \right]^T \tag{2.13}$$

$$\Delta P_{\mathrm{d}}(t) = \left[\Delta P_{\mathrm{d1}}(t) \; \Delta P_{\mathrm{d2}}(t) \; \cdots \; \Delta P_{\mathrm{dn}}(t) \right]^T \tag{2.14}$$

$$A = \left[A_{\mathrm{ij}} \right]_{\mathrm{n \times n}} \tag{2.15}$$

$$B = \mathrm{diag}\left[B_1 \; B_2 \; \cdots \; B_{\mathrm{n}} \right] \tag{2.16}$$

$$C = \mathrm{diag}\left[C_1 \; C_2 \; \cdots \; C_{\mathrm{n}} \right] \tag{2.17}$$

$$F = \mathrm{diag}\left[F_1 \; F_2 \; \cdots \; F_{\mathrm{n}} \right] \tag{2.18}$$

$$B_{\mathrm{i}} = \begin{bmatrix} 0 & 0 & \dfrac{1}{T_{\mathrm{gi}}} & 0 & 0 \end{bmatrix}^T \tag{2.19}$$

$$A_{ii} = \begin{bmatrix} -\frac{D_i}{M_i} & \frac{1}{M_i} & 0 & 0 & -\frac{1}{M_i} \\ 0 & -\frac{1}{T_{chi}} & \frac{1}{T_{chi}} & 0 & 0 \\ -\frac{1}{RT_{gi}} & 0 & -\frac{1}{T_{gi}} & 0 & 0 \\ \theta_i & 0 & 0 & 0 & 1 \\ \sum_{j=1, j\neq i}^{n} T_{ij} & 0 & 0 & 0 & 0 \end{bmatrix} \tag{2.20}$$

$$A_{ij} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ -T_{ij} & 0 & 0 & 0 & 0 \end{bmatrix} \tag{2.21}$$

$$F_i = \begin{bmatrix} -\frac{1}{M_i} & 0 \; 0 \; 0 \; 0 \end{bmatrix}^T \tag{2.22}$$

$$C_i = \begin{bmatrix} \theta_i & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix} \tag{2.23}$$

$$T_{ij} = T_{ji} \tag{2.24}$$

$$\sum_{i=0}^{n} \Delta P_{tiei} = 0 \tag{2.25}$$

$$A = \left[A_{ij} \right]_{n\times n} \tag{2.26}$$

Here, $x(t)\in R^n$ is the state vector, $u(t)$ is the output of the controller. Δf, ΔP_m, ΔP_v, ΔP_d individually represents frequency deviation, generator mechanical power output deviation, control valve position deviation, load deviation. M, D, T_g, R, K_I, K_p individually represent generator moment of inertia, damping coefficient, governor time constant, steam turbine time constant, speed drop coefficient, integral gain, and proportional gain.

In a multi-area system, where there are two or more independently controlled areas in an interconnected power system. Besides controlling the frequency, generation should be controlled in each area to maintain a predetermined power exchange between the areas. Therefore, ACE can be defined as:

$$ACE_{\mathrm{i}} = \theta_{\mathrm{i}} \Delta f_{\mathrm{i}} + \Delta P_{\mathrm{tiei}} \tag{2.27}$$

Here the θ is the frequency deviation factor and ΔP_{tiei} is the net exchanged power deviation on the area i contact line. In addition, the ACE is combined by frequency deviation and net exchange power deviation, which can act as input to the PI controller. Therefore, the output of a PI type load frequency controller for each area using the ACE as input can be expressed as

$$u_{\mathrm{i}}(t) = -K_{\mathrm{pi}} ACE_{\mathrm{i}} - K_{\mathrm{Ii}} \int ACE_{\mathrm{i}} = K_{\mathrm{i}} Y_{\mathrm{i}}\left(t - g(\lambda_{\mathrm{i}})\right) = -K_{\mathrm{i}} C_{\mathrm{i}} x_{\mathrm{i}}\left(t - g(\lambda_{\mathrm{i}})\right) \tag{2.28}$$

Here, K= [K_{pi} K_{Ii}], $K_{\mathrm{pi},}$ and K_{Ii} are respectively the proportional and integral gains of the PI controller. $g(\lambda_{\mathrm{i}})$ represents the AoI of area i, and λ_{i} represents the update rate of area i. The multi-area continuous-time LFC-AoI system can be expressed as

$$\dot{x}(t) = Ax(t) + \sum_{i=1}^{n} A_{\mathrm{di}} x\left(t - g(\lambda_{\mathrm{i}})\right) + F\Delta P_{\mathrm{d}} \tag{2.29}$$

$$A_{\mathrm{di}} = \begin{bmatrix} 0 & \cdots & -B_{\mathrm{i}} K_{\mathrm{i}} C_{\mathrm{i}} & \cdots & 0 \end{bmatrix} \tag{2.30}$$

To simplify the multi-area LFC-AoI model, assume each area has the same AoI. Therefore (2.29) can be simplified below

$$\dot{x}(t) = Ax(t) + A_d x\left(t - g(\lambda)\right) + F\Delta P_{\mathrm{d}} \tag{2.31}$$

$$A_d(t) = \sum_{i=1}^{n} A_{\mathrm{di}} \tag{2.32}$$

According to (2.31), the multi-area continuous-time LFC-AoI model can be dissociated. The discrete-time LFC-AoI model can be shown in **Figure 2.4** expressed as

$$\dot{x}\left(t_{\mathrm{w+1}}\right) = A^{'}x(t_{\mathrm{w}}) + \sum_{a=0}^{b+1} A^{'}_{\mathrm{da}} x(t_{\mathrm{w}} - g(\lambda)) + F^{'}\Delta P_{\mathrm{d}} \tag{2.33}$$

$$\lambda^{-1} = t_{\mathrm{w+1}} - t_{\mathrm{w}} \tag{2.34}$$

$$A^{'} = e^{A\lambda^{-1}} \tag{2.35}$$

$$F^{'} = \lambda^{-1}F \tag{2.36}$$

$$A^{'}_{d\,0} = \ldots = A^{'}_{d\,m-1} = 0 \tag{2.37}$$

$$A^{'}_{\mathrm{db}} = \int_{0}^{(b+1)\lambda^{-1}-g(\lambda)} e^{As} A_{\mathrm{d}} ds \tag{2.38}$$

$$A^{'}_{\mathrm{db+1}} = \int_{(b+1)\lambda^{-1}-g(\lambda)}^{(b+1)\lambda^{-1}} e^{As} A_{\mathrm{d}} ds \tag{2.39}$$

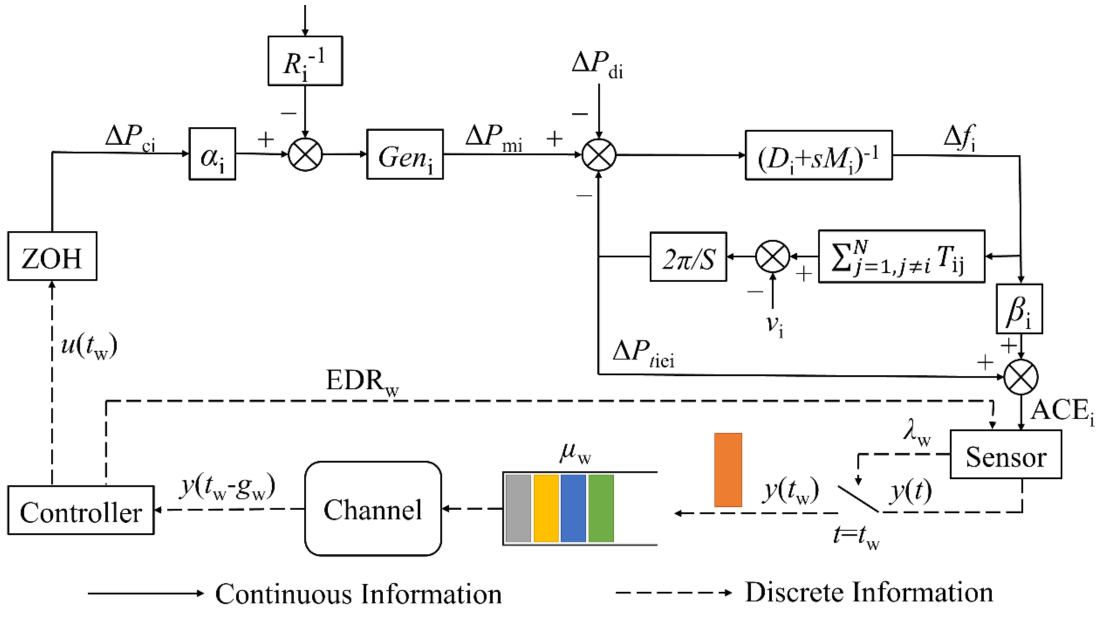

Figure 2.4 Dynamic model of the area *i* LFC system.

2.3 AoI Dependent Stability Criterion for LFC System

(2.5) has shown that an unsuitable update rate will cause the information receiver to accept not fresh information, which even affects the stability of the LFC system. So, it is necessary to ensure the right update rate that can make the LFC system stable.

Studies have shown that stale information can cause the information receiver to make wrong decisions, thus affecting LFC system stability. For example, when the current LFC system's frequency is higher than normal, the unit output should be reduced, but due to the staleness of the information at the information receiver, this information may deliver that the LFC system's frequency is lower than normal, and thus the control center make the decision to increase the unit output, so it does not serve the purpose of adjusting the system's frequency in the presence of continuous small external disturbances, and even lead to the LFC system instability.

In this chapter, a novel AoI-dependent stability criterion for single-area LFC systems is proposed. Based on this criterion, the update rate is determined to guarantee stable LFC system performance. The AoI dependent stability criterion for a single-area LFC system is shown below

Give integers t_1, t_2 satisfying $0<t_1<g<t_2$. If there exist matrices $X>0$, $Y_j>0$ ($j=1, 2, 3$), $J>0$, $K>0$, E_i, F_i, G_i ($i=1, 2$), satisfy the following LMI holds, the discrete LFC system is asymptotically stable for any AoI. Here, $A_d=A_1$

$$\begin{bmatrix} \psi_{11} & \psi_{12} & F_1 & -E_1 & \sqrt{t_h}\,E_1 & \sqrt{t_h}F_1 & \sqrt{t_2}G_1 \\ * & \psi_{22} & F_2 & -E_2 & \sqrt{t_h}\,E_2 & \sqrt{t_h}F_2 & \sqrt{t_2}G_2 \\ * & * & -Y_2 & 0 & 0 & 0 & 0 \\ * & * & * & -Y_3 & 0 & 0 & 0 \\ * & * & * & * & -J-K & 0 & 0 \\ * & * & * & * & * & -J & 0 \\ * & * & * & * & * & * & -K \end{bmatrix} < 0 \tag{2.40}$$

where

$$t_h = t_2 - t_1 \tag{2.41}$$

$$\begin{aligned} \psi_{11} = {} & A^T XA - X + (1+t_h)Y_1 + Y_2 + Y_3 + G_1 + G_1^T \\ & + t_h (A-I)^T J(A-I) + t_2 (A-I)^T K(A-I) \end{aligned} \tag{2.42}$$

$$\begin{aligned} \psi_{12} = {} & A^T XA_1 + t_h (A-I)^T JA_1 - G_1 + G_2^T \\ & + t_2 (A-E)^T KA_1 + E_1 - F_1 \end{aligned} \tag{2.43}$$

Proof. Firstly, when g is an integer, denote $\rho=g=t_1=t_2$. Then, it follows from (2.40) that

$$\begin{bmatrix} \varphi_{11} & \varphi_{12} & F_1 & -E_1 & \sqrt{\rho}G_1 \\ * & \varphi_{22} & F_2 & -E_2 & \sqrt{\rho}G_2 \\ * & * & -Y_2 & 0 & 0 \\ * & * & * & -Y_3 & 0 \\ * & * & * & * & -S \end{bmatrix} < 0 \tag{2.44}$$

where

$$\begin{aligned} \varphi_{11} = {} & A^T XA - X + Y_1 + Y_2 + Y_3 + G_1 + G_1^T \\ & + \rho (A-I)^T K(A-I) \end{aligned} \tag{2.45}$$

$$\varphi_{12} = A^T XA_1 + \rho (A-I)^T KA_1 + E_1 - F_1 - G_1 + G_2^T \tag{2.46}$$

$$\begin{aligned} \varphi_{22} = {} & A_1^T XA - Y_1 + \rho A_1^T KA_1 + E_2 \\ & + E_2^T - F_2 - F_2^T - G_2 - G_2^T \end{aligned} \tag{2.47}$$

$$A^{'} = e^{A\lambda^{-1}} \tag{2.48}$$

From (2.45)–(2.47), it can be easily verified that

$$\begin{bmatrix} \varphi_{11} & \tilde{\varphi}_{12} & \sqrt{\rho}G_1 \\ * & \tilde{\varphi}_{12} & \sqrt{\rho}G_2 \\ * & * & -S \end{bmatrix} < 0 \tag{2.49}$$

where

$$\tilde{\varphi}_{12} = A^T X A_1 + \rho(A-I)^T K A_1 - G_1 + G_2^T \tag{2.50}$$

$$\tilde{\varphi}_{22} = A_1^T X A_1 - Y_1 - Y_2 - Y_3 + \rho A_1^T K A_1 - G_2 - G_2^T \tag{2.51}$$

Applying the Schur complement equivalence to (2.49) yields

$$\varphi = \begin{bmatrix} \varphi_{11} & \tilde{\varphi}_{12} \\ * & \tilde{\varphi}_{22} \end{bmatrix} + \rho \begin{bmatrix} G_1 \\ G_2 \end{bmatrix} K^{-1} \begin{bmatrix} G_1 \\ G_2 \end{bmatrix}^T < 0 \tag{2.52}$$

Now, set $r(t_{\mathrm{k}})=x(t_{\mathrm{k}+1})–x(t_{\mathrm{k}})$ and $Y=Y_1+Y_2+Y_3$. Then, choose a Lyapunov functional candidate for the system (2.33).

$$\begin{aligned} H(k) = x(t_{\mathrm{k}})^T X x(t_{\mathrm{k}}) + \sum_{i=t_{\mathrm{k}}-\rho}^{t_{\mathrm{k}}} x(i)^T Y x(i) \\ + \sum_{j=-\rho}^{-1} \sum_{i=t_{\mathrm{k}}+j}^{t_{\mathrm{k}-1}} r(i)^T K r(i) \end{aligned} \tag{2.53}$$

Then, it can be calculated that

$$\Delta H(k) = H(k+1) - H(k) \le \begin{bmatrix} x(t_{\mathrm{k}}) \\ x(t_{\mathrm{k}} - \rho) \end{bmatrix}^T \varphi \begin{bmatrix} x(t_{\mathrm{k}}) \\ x(t_{\mathrm{k}} - \rho) \end{bmatrix} \tag{2.54}$$

Therefore, together with (2.53), implies that there exists a sufficient small scalar $\beta>0$ such that $\Delta H(k)\le–\beta||x(t_{\mathrm{k}})||^2$. Therefore, the LFC-AoIperformance system in (2.33) is asymptotically stable when $t_1=t_2$. Now, when g is an integer. In this case, a Lyapunov functional candidate is chosen for the system (2.33).

$$H(k) = \sum_{i=1}^{6} H_{\mathrm{i}}(k) \tag{2.55}$$

where

$$H_1(k) = x(t_k)^T X x(t_k) \tag{2.56}$$

$$H_2(k) = \sum_{i=t_k-g}^{t_{k-1}} x(i)^T Y_1 x(i) \tag{2.57}$$

$$H_3(k) = \sum_{i=t_k-t_1}^{t_{k-1}} x(i)^T Y_2 x(i) + \sum_{i=t_k-t_2}^{t_{k-1}} x(i)^T Y_3 x(i) \tag{2.58}$$

$$H_4(k) = \sum_{i=-t_2+(t_{k+1}-t_k)}^{-t_1} \sum_{i=t_k+j}^{t_{k-1}} x(i)^T Y_1 x(i), \tag{2.59}$$

$$H_5(k) = \sum_{i=-t_2}^{-t_1-(t_{k+1}-t_k)} \sum_{i=t_k+j}^{t_{k-1}} r(i)^T J r(i) \tag{2.60}$$

$$H_6(k) = \sum_{i=-t_2}^{-(t_{k+1}-t_k)} \sum_{i=t_k+j}^{t_{k-1}} r(i)^T K r(i). \tag{2.61}$$

Donate, when $g \neq t_2$

$$\phi_1(k) = x(t_k - g) - x(t_k - t_2) - \sum_{i=t_k-t_2}^{t_{k-1}-g} r(i) \tag{2.62}$$

When $g = t_2$:

$$\phi_1(k) = x(t_k - g) - x(t_k - t_2) \tag{2.63}$$

When $g \neq t_1$:

$$\phi_2(k) = x(t_k - t_1) - x(t_k - g) - \sum_{i=t_k-g}^{t_{k-1}-t_1} r(i) \ , \tag{2.64}$$

When $g = t_1$:

$$\phi_2(k) = x(t_k - t_1) - x(t_k - g) \tag{2.65}$$

$$\phi_3(k) = x(t_k) - x(t_k - g) - \sum_{i=t_k-g}^{t_{k-1}} r(i) = 0 \tag{2.66}$$

Then, it is obvious that $\phi_1(k)$=0, $\phi_2(k)$=0 and $\phi_3(k)$=0. By some simple manipulations, there is

$$\begin{aligned}\Delta H(k) = {} & [2x(t_k)^T E_1 + 2x(t_k - g)^T E_2]\phi_1(k) \\ & + [2x(t_k)^T F_1 + 2x(t_k - g)^T F_2]\phi_2(k) \\ & + [2x(t_k)^T G_1 + 2x(t_k - g)^T G_2]\phi_3(k) \\ & + \sum_{i=1}^{6} \Delta H_i(k) \le \xi(k)^T \Theta \xi(k)\end{aligned} \tag{2.67}$$

where

$$\xi(k) = [x(t_k)^T \; x(t_k - g)^T \; x(t_k - t_1)^T \; x(t_k - t_2)^T]^T \tag{2.68}$$

$$\Theta = \phi + t_h E_{11}(J+K)^{-1} E_{11}^T + t_h F_{11} J^{-1} F_{11}^T + t_2 G K^{-1} G^T \tag{2.69}$$

$$\phi = \begin{bmatrix} \psi_{11} & \psi_{12} & F_1 & -E_1 \\ * & \psi_{22} & F_2 & -E_2 \\ * & * & -Y_2 & 0 \\ * & * & * & -Y_3 \end{bmatrix} \tag{2.70}$$

$$E_{11} = [E_1^T \; E_2^T \; 0 \; 0]^T \tag{2.71}$$

$$F_{11} = [F_1^T \; F_2^T \; 0 \; 0]^T \tag{2.72}$$

$$G = [G_1^T \; G_2^T \; 0 \; 0]^T \tag{2.73}$$

Applying the Schur complement equivalence to (2.69) leads to Θ<0. This, together with (2.70), implies that there exists a sufficient small scalar β>0 such that $\Delta H(k) < -\beta \|x(t_k)\|^2$Therefore, the discrete-time LFC system in (2.33) is asymptotically stable when $0<t_1<g<t_2$.

2.4 Summary of Analysis Steps

Detailed implementation of the method proposed is shown as the following:

Step1): Modeling LFC-AoI system performance

Step2): Simulation. Based on the detailed model obtained in Step 1, the simulation method is used to find if a given update rate can make the LFC system stable by observing the stability of the LFC system. Here, if the frequency deviation is smaller than 0.05Hz after the 30s, the LFC system is regarded as stable.

Step3): Determining update rate range. Based on the detailed model obtained in Step 1, Repeat step 2) by gradually increasing the update rate in small increments to find the update rate range which can guarantee the LFC performance stability.

2.4 Result and Discussion

In the present work, in order to show the maximum AoI that can make the LFC system performance stable. There is a one-area load frequency control system, its specific parameters are shown in **Table 2.1**.

Table 2.1 Parameters of the LFC system.

Parameter	M	D	β	T_g	T_{ch}	R
Value	10	1.0	21.0	0.1	0.3	0.05

According to the LFC-AoI performance model (2.33), maximum AoI can be found, which will lead to stable LFC system performance. Furthermore, based on (2.5), for the first-come-first-served (FCFS) M/M/1 system, the relationship between AoI and update rate is a convex function, so the maximum update rate and minimum update rate also can be found corresponding to this maximum AoI. The results are illustrated in **Table 2.2.**

This chapter will analyze in detail the impact of the information update rate on the performance of the LFC system when the proportional gain of the PI controller K_p and integral gain of the PI controller K_I is equal to 0.2. **Table 2.2** also has shown the range of update rates of this LFC system. Here three cases are discussed. The first one is the actual update rate λ is low than the minimum update rate λ_{min} ($\lambda<\lambda_{min}$); the second one is the actual update rate λ is faster than the maximum update rate λ_{max} ($\lambda<\lambda_{max}$); the actual update rate λ is in the range of update rate ($\lambda_{min}<\lambda<\lambda_{max}$).

Table 2.2 Maximum AoI and update frequency range for different LFC systems.

K_I	K_p											
	0			***0.05***			***0.1***			***0.2***		
	g_{max}	f_{max}	f_{min}	g_{max}	f_{max}	f_{min}	g_{max}	f_{max}	f_{min}	g_{max}	f_{max}	f_{min}
0.05	29.44	1.04	28.44	30.44	1.03	29.44	31.42	1.03	30.42	32.58	1.03	31.58
0.1	14.77	1.07	13.76	15.25	1.07	14.24	15.72	1.07	14.72	16.45	1.07	15.45
0.15	9.77	1.12	8.76	10.09	1.11	9.08	10.38	1.11	9.37	10.91	1.10	9.90
0.2	7.24	1.17	6.21	7.49	1.16	6.46	7.68	1.16	6.65	8.05	1.15	7.03

2.4.1 When $\lambda<\lambda_{min}$

The actual update rate λ is low than the minimum update rate λ_{min} ($\lambda<\lambda_{min}$). Its simulation results are shown in **Figure 2.5.**

When the update rate is 1.14s/sec (update every 1.14s on average), which is faster than the maximum update frequency. Hence, the load frequency tends to disperse which means the LFC system performance becomes unstable. If we continue to accelerate the update frequency to 1.13s/sec, which makes the load frequency dispersion to be more powerful, that represents the LFC system performance becoming more unstable.

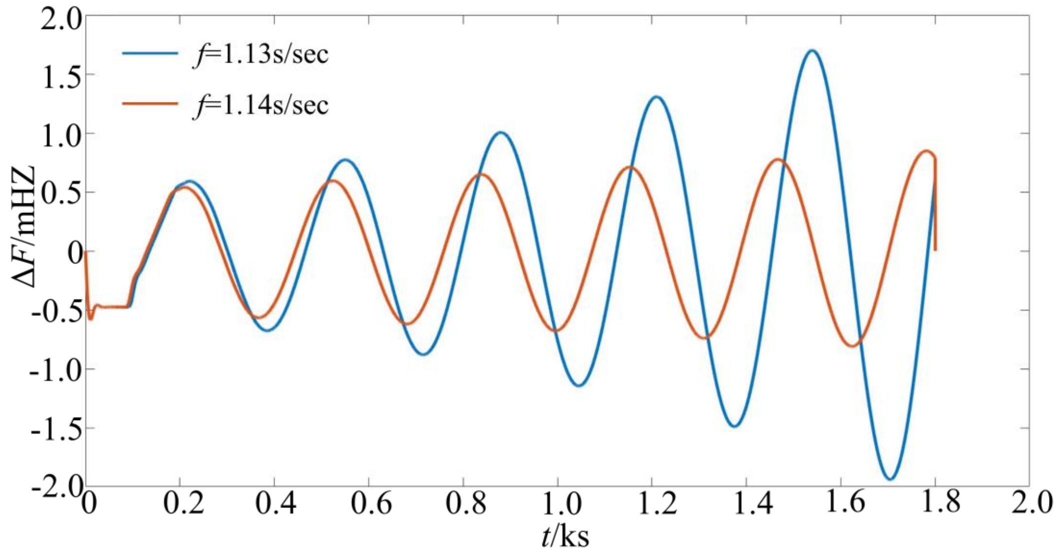

Figure 2.5 LFC system responds when $f>f_{max}$.

2.4.2 When $\lambda<\lambda_{min}$

The actual update rate λ is faster than the maximum update rate λ_{max} ($\lambda<\lambda_{max}$). Its simulation results are shown in **Figure 2.6.**

When the update frequency is 7.20s/sec, which is slower than the minimum update frequency. As a result, the load frequency tends to disperse and the LFC system performance becomes unstable. If we continue to lower the update frequency to 7.50s/sec, which makes the load frequency dispersion to be more powerful, and the LFC system performance becomes more unstable.

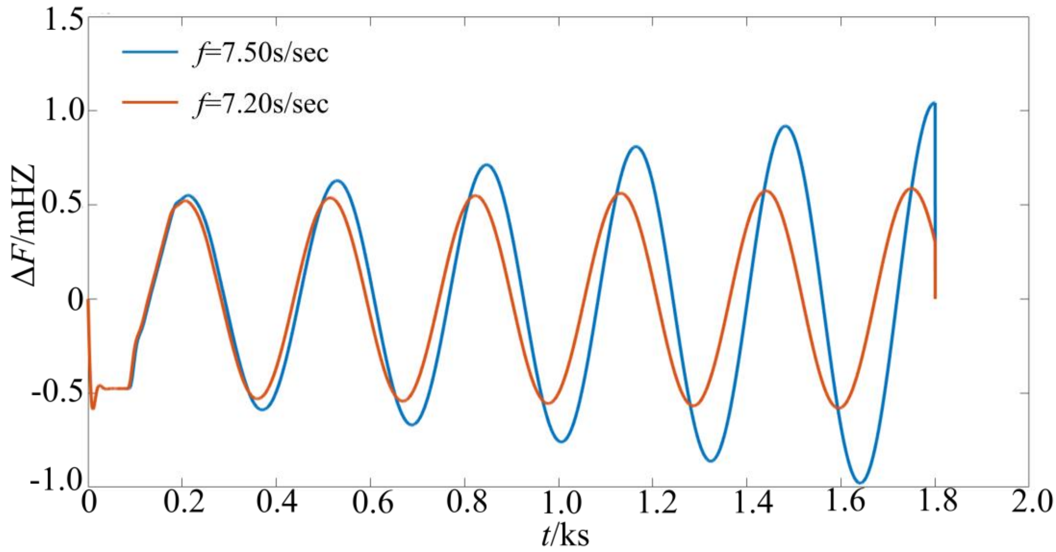

Figure 2.6 LFC system responds when $f<f_{\min}$.

2.4.3 When $\lambda_{min}<\lambda<\lambda_{max}$

The actual update rate λ is in the range of update rate ($\lambda_{\min}<\lambda<\lambda_{\max}$). Its simulation results are shown in **Figure 2.7**.

If we pick one of the update frequencies 5.50s/sec in the update frequency range, the load frequency can converge, and the LFC system performance keeps stable. From the above three cases, the frequency of information updates has a significant impact on the stability of LFC system performance. Hence, it is important to get the range of LFC system update frequency, which can ensure the stability of LFC system performance.

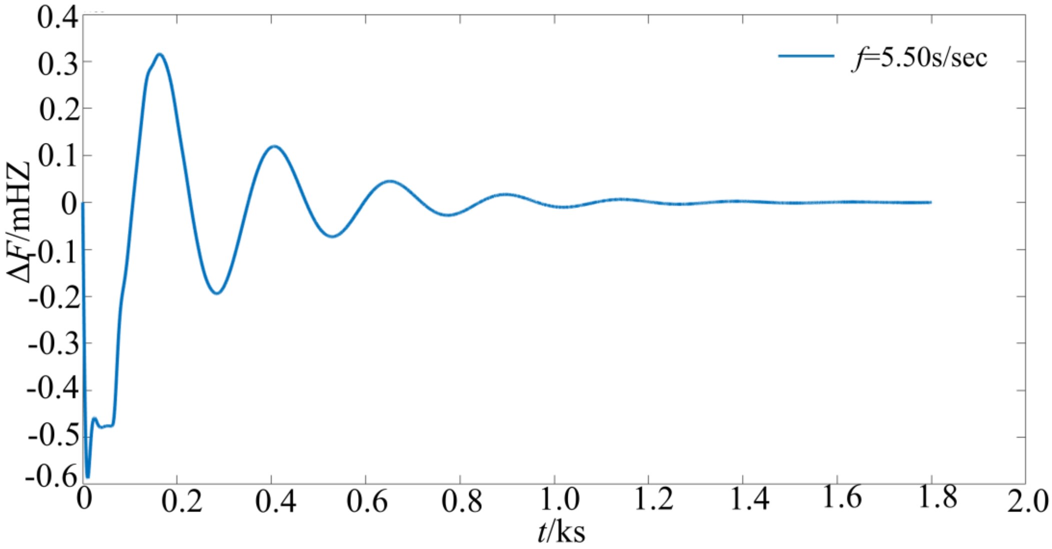

Figure 2.7 LFC system responds when $f<f_{\min}$.

2.5 Conclusion

In this chapter, we introduce the concept of AoI into the field of communication into the stability analysis of LFC systems, which accurately portrays the effect of the freshness of the information packet for the information receiving end on the stability of LFC systems, and design an LFC-AoI system performance model, that reflects the impact of update frequency on LFC system's AoI and LFC system performance. In addition, we create an AoI depending on the single-area LFC system stability criterion. The case studies are based on a single-area LFC system, which shows the effect of update frequency and AoI on the stability of the LFC system and finds the maximum AoI and update frequency range that can make the performance of the LFC system stable.

Chapter 3 Stability Analysis of Load Frequency Control Based on Age-of-Information

Based on the LFC-AoIsystem model in chapter 2. This chapter shows that the AoI margin is different from the delay margin. AoI margin depends on the information freshness and the update rate of the communication system. The delay margin is determined by the information packet staleness. Therefore, for a single-area LFC system, the AoI margin is a two-dimensional space while the delay domain is a one-dimensional space. The calculation of the AoI margin is very challenging because it should consider the update rate. To illustrate the impact of update rate on AoI margin, this chapter introduces the structure of the communication system and the communication queue model.

The contribution of this chapter is to propose the AoI margin and compare it with the communication delay margin.

3.1 Delay and AoI

As research progresses, the delay model in LFC systems becomes more complex and the simulations are more accurate. However, the communication delay is a physical index that only describes the transmission time of each packet in the channel and portrays the degree of staleness of each packet. Therefore, it does not portray the process of updating information and cannot fully capture the information freshness paradigm. For example, when the information update rate is high, no phenomenon such as congestion occurs in the channel and the delay of the information packet is small. However, too high an information update rate leads to a lack of fresh enough information for the information receiver to make appropriate frequency modulation decisions. Hence, the delay only characterizes the staleness of each information packet in the transmission process but does not characterize if the information receiver gets fresh information regularly.

In addition, studies have shown that stale information will lead the information receiver to make inaccurate frequency modulation decisions, so it is necessary to portray the information freshness to the information receiver. Therefore, just portraying the delay of each information packet freshness degree does not satisfy this requirement.

Because of this, scholars in the information field have defined a metric of information freshness [13], called AoI. It describes the information freshness of the information receiving end. Although both delay and AoI are indexes that portray the degree of staleness, they are described by different objects. Communication delay is a packet-centric index that portrays the degree of staleness of each information packet, while AoI is an information receiver-centric index that portrays the immediacy of the entire information update, which can be used to assess the impact of the information update process on the physical grid.

In addition, AoI reveals the impact of update rate on the information freshness, which changes the perception of information systems. In particular, in the existing perception of power systems, the information packets' arrival is considered an exogenous process that cannot be controlled. However, updating information at the right rate may be more efficient [13]. For example, while a high update rate can lead to short queuing delays, the control center may end up with stale information due to infrequent updates. On the other hand, a low update rate can result in information becoming stale over a long queue.

Although both delay and AoI are indexes that portray the degree of staleness, they are described for different objects, definitions, modes, properties, and margins in a communication system. **Table 3.1** shows the detailed difference between AoI and delay in these aspects. **Figure 3.1** illustrates the model difference between the delay of the information packet and information's AoI for the information receiver.

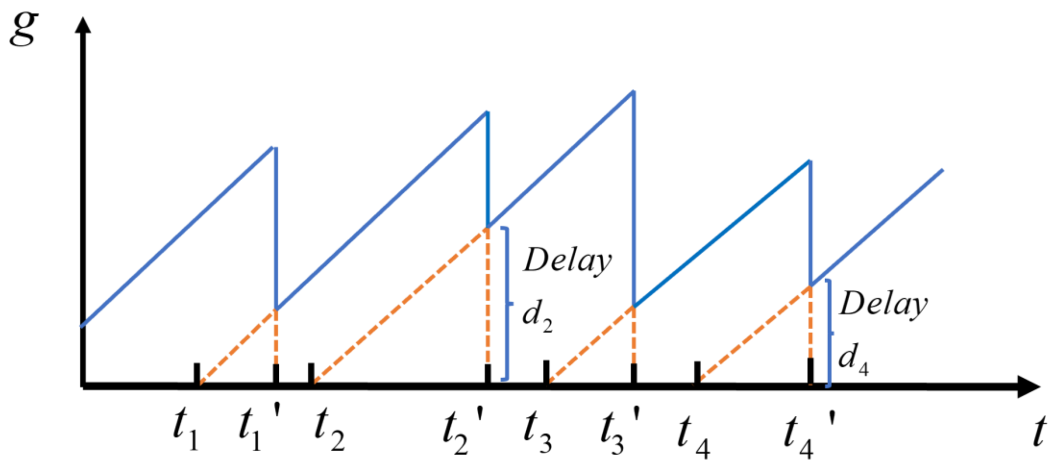

Figure 3.1 Evolution of the AoI and information packet's delay.

The information packet *k* is generated at t_k, and is received at t_k'. When the information receiver gets the *k* th information packet, the value of AoI decline to d_k, which turns out to be the communication delay of the *k* th information packet. **Figure 3.1** shows that AoI always grows from the delay of the information packet. Theoretically, for the same LFC, its AoI margin is larger than the delay margin.

Table 3.1 Differences between AoI and delay.

	AoI	Delay
Object	Information update process	Each information pocket
Definition	$AoI = t - \max\{t_k : t_k' < t\}$	$Delay = t_k' - t_k$
Model	Queue model	Random sequence
Property	AoI can be controlled by the update rate	Delay is an uncontrolled exogenous sequence
Margin	AoI margin is determined by transmission time and update rate of information	The Delay margin is determined by the transmission time of information

Firstly, the communication delay is a packet-centric index that portrays the degree of staleness of each information packet, while AoI is an information receiver-centric index that portrays the immediacy of the whole information update process, which can be used to assess the impact of the information update process on the physical grid. Secondly, the delay is considered an uncontrolled exogenous sequence; however, AoI can be described by a queueing model so the update rate can control it. Thirdly, the delay margin is only determined by the transmission time of information, but AoI margin is determined by not only transmission time but also the update rate of information. The information freshness in real-time is equal to the minimization of AoI, instead of the minimization of communication delay.

3.2 The model of LFC-AoI and LFC-delay

In this chapter, a one-area LFC-AoIsystem model is constructed, which reflects the impact of the AoI of the information for the information receiver on LFC system performance. Based on Chapter II, the discrete model of the single-area LFC system with delay can be expressed as:

$$x(t_{\mathrm{w+1}}) = A'x(t_{\mathrm{w}}) + \sum_{n=0}^{m+1} B_{\mathrm{n}}^{'} x(t_{\mathrm{w}} - d_{\mathrm{k}}) + F'\Delta P_{\mathrm{d}} \tag{3.1}$$

$$h = t_{\mathrm{w+1}} - t_{\mathrm{w}} \tag{3.2}$$

$$A' = e^{Ah} \tag{3.3}$$

$$F' = hF \tag{3.4}$$

$$B_0' = \ldots = B_{m-1}' = 0 \tag{3.5}$$

$$B_{\mathrm{m}}^{'} = \int_0^{(m+1)h-d_{\mathrm{k}}} e^{As} B ds \tag{3.6}$$

$$B_{\mathrm{m+1}}^{'} = \int_{(m+1)h-d_{\mathrm{k}}}^{(m+1)h} e^{As} B ds \tag{3.7}$$

Here, *h* is the sampling period, and d_{k} is randomly generated values within the delay range. [19] shows that in an open communication system, the delay of an LFC system can vary in the interval [0.15, 2] seconds.

The discrete model of the single-area LFC-AoIsystem can be expressed as:

$$x(t_{\mathrm{w+1}}) = A''x(t_{\mathrm{w}}) + \sum_{n=0}^{m+1} B_{\mathrm{n}}^{''} x(t_{\mathrm{w}} - g(\lambda)) + F''\Delta P_{\mathrm{d}} \tag{3.8}$$

$$\lambda^{-1} = t_{\mathrm{w+1}} - t_{\mathrm{w}} \tag{3.9}$$

$$A'' = eA^{\lambda^{-1}} \tag{3.10}$$

$$F'' = \lambda^{-1} F \tag{3.11}$$

$$B_0'' = \ldots = B_{m-1}'' = 0 \tag{3.12}$$

$$B_m^{''} = \int_0^{(m+1)\lambda^{-1}-g(\lambda)} e^{As} B ds \tag{3.13}$$

$$B_{m+1}^{''} = \int_{(m+1)\lambda^{-1}-g(\lambda)}^{(m+1)\lambda^{-1}} e^{As} B ds \tag{3.14}$$

$$g(\lambda) = \frac{1}{\mu}(1+\frac{\mu}{\lambda}+\frac{\lambda^2}{\mu^2-\mu\lambda}) \tag{3.15}$$

$$x(t_{\mathrm{w}}) = \left[\Delta f \ \Delta P_{\mathrm{m}} \ \Delta P_{\mathrm{v}} \ \int \alpha \Delta f \right]^T \tag{3.16}$$

(13) introduces delay as an uncontrolled exogenous sequence, so the communication system can randomly select the update rate. On the other hand, (17) shows that AoI is relative to the update rate, which can be used to assess the impact of the information update process on the LFC system.

3.3 Difference Between AoI Margin and Delay Margin

This chapter illustrates the difference between the AoI margin and delay margin and shows the superiority of the AoI margin over the delay margin for the LFC system. The difference between AoI margin and delay margin is presented in **Table 3.2**.

Table 3.2 Differences between AoI margin and delay margin.

	AoI margin	Delay margin
Definition	how stale information is received by the LFC system before it becomes unstable?	how long transmission time of information packets are received by the LFC system before it becomes unstable.
Influencing Factors	Transmission time and update rate	Only transmission time
Dimensionality	Two–dimensional space	One–dimensional space

	AoI margin	Delay margin
Property	AoI margin can be controlled by the update rate.	The Delay margin is uncontrolled

Firstly, AoI describes how stale information is received by the LFC system before it becomes unstable. The delay margin shows how long the transmission time of information packets is received by the LFC system before it becomes unstable. Secondly, the AoI margin is a two–dimensional space, which is influenced by both transmission time and update rate; the delay margin is a–dimensional space, which is only influenced by transmission time.

The difference between the AoI margin and delay margin is because the AoI margin considers the whole information update process while the delay margin does not. Therefore, when the update period λ^{-1} of the LFC-AoI system is equal to the sampling period h of delay–in the LFC system, the AoI margin is larger than the delay margin. In addition, with different update rates, the delay margin is constant, but the AoI margin is different.

Both AoI margin and delay margin are indexes that guarantee the LFC system to be stable. However, the superiority of the AoI margin over the delay margin for the LFC system is also relevant to the object. AoI margin considers the whole information process expanding the domain from one-dimensional space to two-dimensional space, realizing the control of the AoI domain. Furthermore, AoI margin describes how stale information can be received by the information receiver to the LFC system before it becomes unstable.

3.4 Result and Discussion

Case studies for the single-area LFC-AoImodel were carried out to assess the AoI margin. The difference between AoI margin and delay margin can be shown in (13) and (17). The parameters of a single–area power system are given in **Table 3.3**.

Table 3.3 Parameters of the LFC system.

Parameter	M	D	β	T_g	T_{ch}	R
Value	10	1.0	21.0	0.1	0.3	0.05

3.4.1 The Maximum AoI

The cases analyzed in detail the impact of information freshness on the performance of the LFC system when the proportional gain of the PI controller K_p and integral gain of the PI controller K_I are equal to 0.2. A positive load disturbance ΔP_d = 0.1 is constantly added to the system.

Simulation results indicate that the maximum AoI of this LFC system is 9.16 seconds. **Figure 3.2** shows that the single-area LFC system is stable at the obtained value of 9.16 s. On contrary, **Figure 3.3** shows that the single-area LFC system becomes unstable if AoI is larger than the maximum AoI.

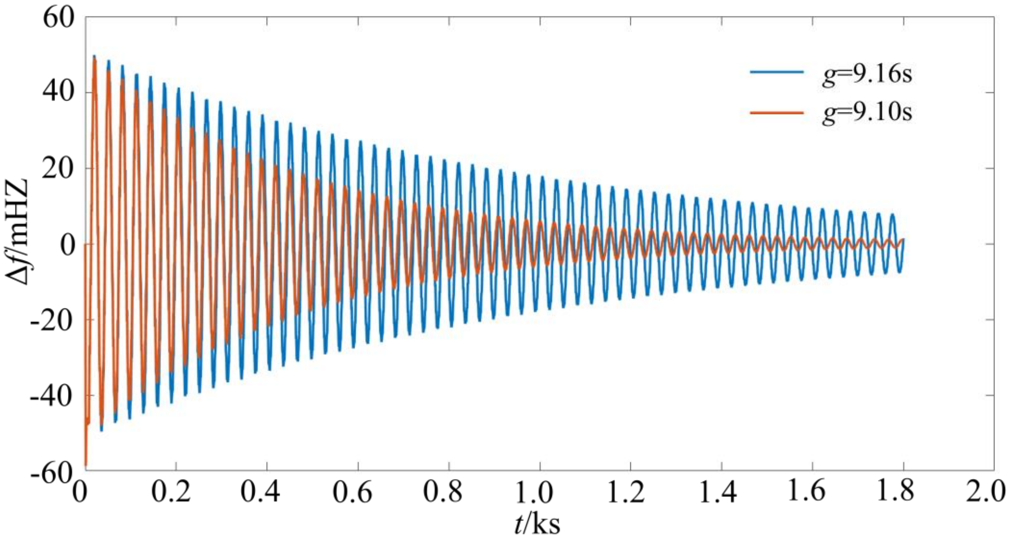

Figure 3.2 LFC performance of the proposed LFC-AoImodel in a single-area power system (K_p=0.2, K_I=0.2) when $g \in$AoI margin.

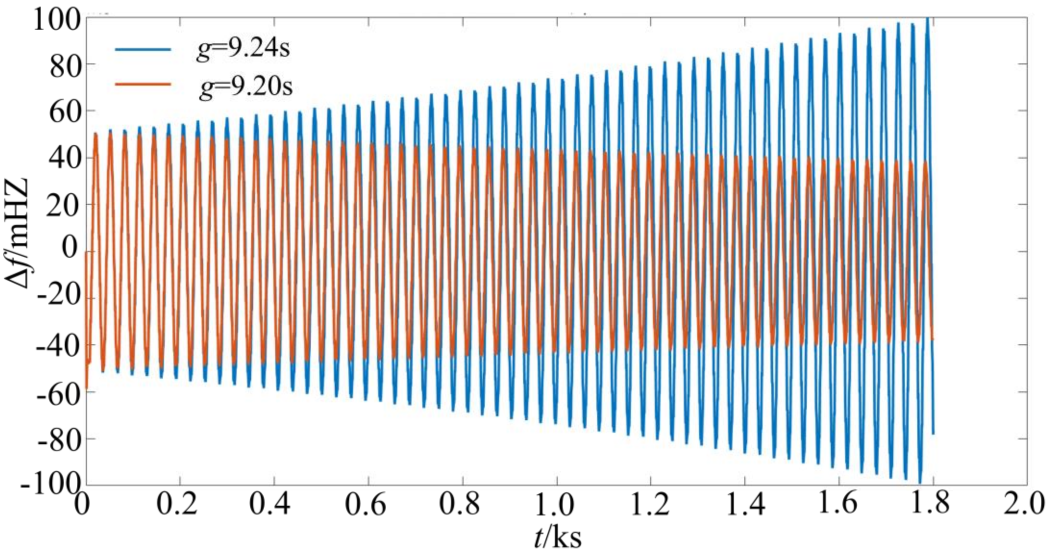

Figure 3.3 LFC performance of the proposed LFC-AoImodel in a single-area power system(K_p=0.2, K_I=0.2) when $g \notin$AoI margin.

Simulation results indicate that the maximum AoI of this LFC system is 9.16 seconds. **Figure 3.2** shows that the single-area LFC system is stable at the obtained value of 9.16 s. On contrary, **Figure 3.3** shows that the single-area LFC system becomes unstable if AoI is larger than the maximum AoI.

3.4.2 AoI Margin and Delay Margin

(3) shows that AoI margin is also influenced by update rate. To compare AoI margin and delay margin, the sampling period of the delay–LFC system and the update period of the LFC-AoIsystem should remind consistently. In the test, for the delay–LFC model, the sampling period is h=2 seconds; for LFC-AoImodel, the update period is also λ^{-1}=2 seconds. Time-domain simulation of the LFC systems is undertaken in MATLAB/Simulink to show the delay margin and AoI margin. This comparison is provided in **Table 3.3.**

The simulation results show that the AoI margin is about 2 seconds larger than the delay margin, and the sampling period of the delay–LFC system and the update period of the LFC-AoIsystem are also equal to 2 seconds. This is coinciding with the theoretical study because packet–centric delay does not consider the whole information update process. So, if the sampling period of the delay–LFC system and the update period of LFC-AoIsystem are equal to 3 seconds, the AoI margin should be about 3 seconds larger than the delay margin.

AoI is decided not only by transmission time but also by update rate. The text analyzes in detail the impact of update rate on AoI margin in K_P=0.2, K_I=0.2 LFC system.

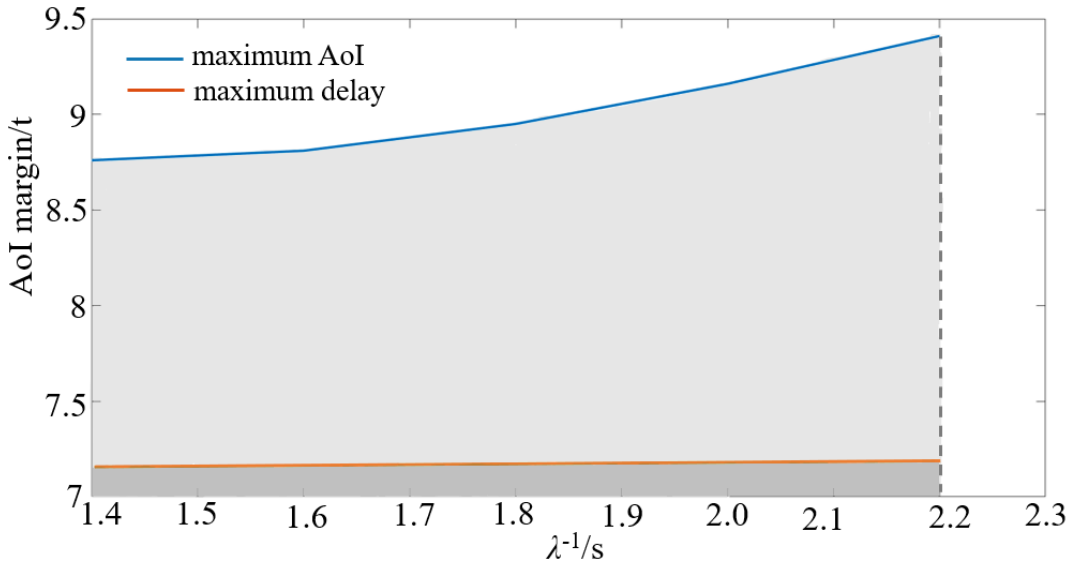

Figure 3.4 The AoI margin of a single-area LFC system(K_p=0.2,K_I=0.2)

The AoI domain refers to the area of the region that is equal to {1.4s≤λ^{-1}≤2.2s; 0<AoI<maximum AoI} in **Figure 3.4**. The delay domain refers to the area of the region that is equal to {1.4s≤λ^{-1}≤2.2s; 0<AoI<maximum delay} in **Figure 3.4**. Firstly, the delay margin is constant with different update rates. The AoI margin increases when the update period λ^{-1} grows. The infrequent update leads to a larger AoI margin. Secondly, **Figure 3.4** illustrates that–the dimensional delay margin is a part of the two–dimensional AoI margin. Since the delay domain will not be controlled by the update rate, the delay domain can be seen as a special case of the AoI domain. **Table 3.4** details the difference between AoI margin and Delay margin.

Table 3.4 AoI domain and communication delay domain.

***K*I**	***K*p**									
	0		***0.05***		***0.1***		***0.2***		***0.4***	
0.05	30.46	28.47	31.44	29.45	32.44	30.45	33.69	31.52	35.89	33.32

***K*I**	***K*p**									
	0		***0.05***		***0.1***		***0.2***		***0.4***	
0.1	15.99	13.81	16.48	14.32	16.97	14.8	17.45	15.44	18.8	16.64
0.15	10.83	8.84	11.16	9.17	11.4	9.38	11.79	9.74	12.92	10.86
0.2	8.34	6.33	8.6	6.58	8.83	6.82	9.17	7.16	9.4	7.39
0.4	4.53	2.53	4.65	2.65	4.77	2.77	4.98	2.96	5.17	3.17
0.6	3.04	1.05	3.12	1.12	3.19	1.19	3.28	1.28	3.36	1.37
1	2.39	0.4	2.44	0.45	2.49	0.5	2.59	0.6	2.76	0.79

3.5 Conclusion

This chapter explains the difference between AoI and delays from object, definition, model, property, and margin. Delay only describes the staleness of each information packet, but AoI describes the whole information update process, which accurately presents the information freshness.

The case demonstrates the AoI margin of the single-area LFC system and shows the information freshness impact on LFC performance. Simulation results also demonstrate that the AoI margin is larger than the delay margin and the large extent depends on the update rate.

Chapter 4 Age-of-Information-Aware Load Frequency Control

In a modern power system, the LFC needs a better robustness performance, because of the uncertainties of the parameters, stability issues, and low inertia. Recently, according to advanced control methods, like sliding mode control [25, 26], active disturbance rejection control [27], model-based control [28] and model predictive control [29]. The power system employs some robust LFC schemes. But the above control methods cause complex state feedback or high order controllers. [30] shows that the PID-type controller is still preferred by power systems.

Based on the LFC-AoI model in chapter 1, This chapter optimizes the performance of the LFC system by designing a robust PI-based LFC scheme and an updated schedule. the advanced LFC scheme considers both the effect of the update rate and the AoI for the controller. And the update schedule means choosing the right update rate.

The contributions of this chapter include demonstrating the PI-type controller and update rate which optimize the performance of LFC.

4.1 Conclusion Design of PI controller based on update rate

Based on the normal multi-area LFC-AoI model and the criterion and robust performance analysis conditions, a design method of the robust PI LFC scheme is introduced.

To design a robust PI LFC scheme, EDR m is considered. and update rate λ is considered to design a PI controller with design robustness performance. The following algorithm is introduced.

Theorem 1： Consider LFC-AoI system (27) with ΔP_d=0. When given update rate λ, EDR m, and turning parameters e and l, 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 W satisfy the following inequalities hold

$$\Theta_{1j} = \varphi_1 + \Gamma_j + \lambda^{-1}\varphi_2 < 0, j = 1,2 \tag{4.9}$$

$$\Theta_{2j} = \begin{bmatrix} \varphi_1 + \Gamma_j & -\lambda^{-1}\Psi_2^T W \\ * & -\lambda^{-1}Z \end{bmatrix} < 0 \tag{4.9}$$

$$\begin{aligned} \varphi_1 = {} & Sym\left\{ \begin{bmatrix} c_1 \\ c_3 \end{bmatrix}^T P_1 \begin{bmatrix} c_5 \\ c_4 \end{bmatrix} + \psi_2^T W\left(c_1 - c_2\right) \right\} \\ & - \begin{bmatrix} c_3 \\ c_2 \end{bmatrix}^T X \begin{bmatrix} c_3 \\ c_2 \end{bmatrix} + \begin{bmatrix} c_1 \\ c_5 \end{bmatrix}^T P_2 \begin{bmatrix} c_1 \\ c_5 \end{bmatrix} - \begin{bmatrix} c_3 \\ c_4 \end{bmatrix}^T P_2 \begin{bmatrix} c_3 \\ c_4 \end{bmatrix} \\ & + g(\lambda) c_5^T P_3 c_5 - \frac{1}{g(\lambda)}\left(c_1 - c_3\right)^T P_3 \left(c_1 - c_3\right) \end{aligned} \tag{4.9}$$

$$\Gamma_j = \psi_1^T \psi_3 \left(S^T c_5 - \left(A^{'} + mI\right) S^T c_1 - \eta_j BYc_2 \right) \tag{4.9}$$

$$X = \begin{bmatrix} X_1 + X_1^T & -X_1 - X_2 \\ \left(-X_1 - X_2\right)^T & X_2 + X_2^T \end{bmatrix} \tag{4.9}$$

$$\varphi_2 = c_4^T Z c_4 + Sym\left\{ \begin{bmatrix} c_3 \\ c_2 \end{bmatrix}^T X \begin{bmatrix} c_4 \\ 0 \end{bmatrix} \right\} \tag{4.9}$$

$$c_\varepsilon = \left[0_{\zeta\times(\varepsilon-1)\zeta} \; I_\zeta \; 0_{\zeta\times(5-\varepsilon)\zeta} \right], \varepsilon = 1,\ldots,5 \tag{4.9}$$

$$\psi_1 = \left[c_1^T \; c_2^T \; c_5^T \right]^T \tag{4.9}$$

$$\psi_2 = \left[c_1^T \; c_2^T \; c_3^T \; c_4^T \; c_5^T \right]^T \tag{4.9}$$

$$\eta_1 = e^{mg(\lambda)} \tag{4.9}$$

$$\eta_2 = e^{m\left(g(\lambda)+\lambda^{-1}\right)} \tag{4.9}$$

ζ is the dimension of matrix $A^{'}$ in the LFC-AoI system (27). Then any update rate λ that leads g to be smaller than $g(\lambda)$ can keep the LFC-AoI system stable with EDR m. In addition, the gain of the PI controller can be calculated as

$$K_{\mathrm{i}} = Y\left(S^{T}\right)^{-1} C_{\mathrm{i}}^{T} \left(C_{\mathrm{i}} C_{\mathrm{i}}^{T}\right)^{-1} \tag{4.9}$$

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

Theorem 2: In order to show the robustness performance of the calculated PI controller, the H_∞ performance analysis condition is presented. Here γ is introduced to present H_∞ performance. Consider the LFC-AoI system (27) with $\Delta P_d \neq 0$. When given H_∞ performance γ, the following inequality holds

$$\Omega_1 = \begin{bmatrix} \Theta_1 & -\psi_1^T LF \\ * & -\gamma I \end{bmatrix} < 0 \tag{4.9}$$

$$\Omega_2 = \begin{bmatrix} \Theta_2 & \begin{bmatrix} -\psi_1^T LF \\ 0 \end{bmatrix} \\ * & -\gamma I \end{bmatrix} < 0 \tag{4.9}$$

Then any update rate λ that leads g to be smaller than $g(\lambda)$ can keep the LFC-AoI system stable with load disturbance ΔP_d and H_∞ performance γ. $c_1^T C^T C c_1$ should be added into φ_1 and the other matrix notations are the same as Theorem 1.

4.2 The algorithm for designing a PI-type LFC scheme

For a given allowable update rate λ. The average AoI at λ in the FCFS M/M/1 system is $g(\lambda)$. Consider the $H\infty$ performance γ. An algorithm is shown below to design a PI-type controller with desired LFC performance.

Algorithm 1: Find EDR m_{test} and PI-type controller gain K_{test}

Given λ, $g(\lambda)$, γ, and search interval [m_{min}, m_{max}] with m_{min}=0 and sufficiently large m_{max}>m, the accuracy coefficient m_{ac} = 0.001.

m_{test}= (m_{min}+ m_{max})/2

If the LMIs (31) and (32) are feasible then

Compute K_{test} by equation (42).

Bring K_{test} into Theorem 2 with γ

Repeat

If the LMIs (43) and (44) 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_{test} and m_{test}

4.3 Result and discussion

In this chapter, case studies are based on a one-area LFC system. The necessity of introducing AoI to the LFC study is verified by evaluating the effect of the update rate on LFC performance. The correctness of the design of the PI-type controller and update schedule is also verified by comparing the LFC performance under different PI controllers and update rates.

Parameters of a one-area LFC system are reported in Table I. To show the necessity of considering both information freshness and update rate to LFC performance, the LFC performance under different update rates are compared. The degree of load frequency fluctuation W represents the LFC performance. Here FCFS M/M/1 system is considered, and the relationship between AoI and update rate λ is illustrated in (2.5). By setting K_p=0.2, K_I=0.2, T_1=1800s, and following a one-area LFC-AoI system, the LFC system performance is tested in the presence of load disturbance ΔP_d=0.01 for $t \geq 0$. The variation of LFC system performance W with update rate λ can be obtained in

Table 4.1 Parameters of the LFC system.

Parameter	M	D	β	T_g	T_{ch}	R
Value	0.2	0.01	0.51	0.08	0.3	2.00

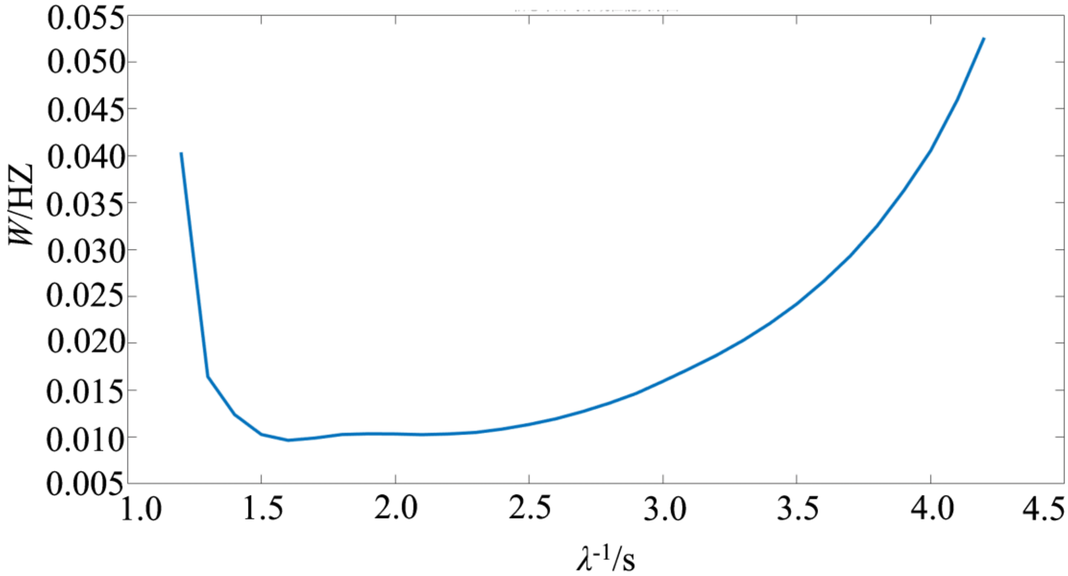

Figure 4.1 Performance of one-area LFC-AoI system under different update rates

It can be seen from **Figure.4.1** that LFC performance and update rate are proportionally related. This allows us to find the right update rate for optimal performance directly. As the update frequency grows from λ^{-1}= 1.2s, the LFC performance generally rapidly becomes better, and the update frequency at λ^{-1}= 1.6s is a critical point for optimal LFC performance. However, when update frequency continues to grow from λ^{-1}= 1.6s to λ^{-1}= 4.2s, the worse LFC performance is obtained.

This result verifies that both too high or too low update rates significantly deteriorate the LFC performance, and it can be optimized by adjusting the update rate.

Under different update rates, responses of the frequency deviation Δ*f* are shown in **Figure 4.2**. **Figure 4.2 (a)** shows that Δ*f* with λ^{-1}=1.2s and 1.4s cause larger fluctuations than that with λ^{-1}=1.6s. And λ^{-1}=1.2s results in larger Δ*f* fluctuations than λ^{-1}=1.4s.

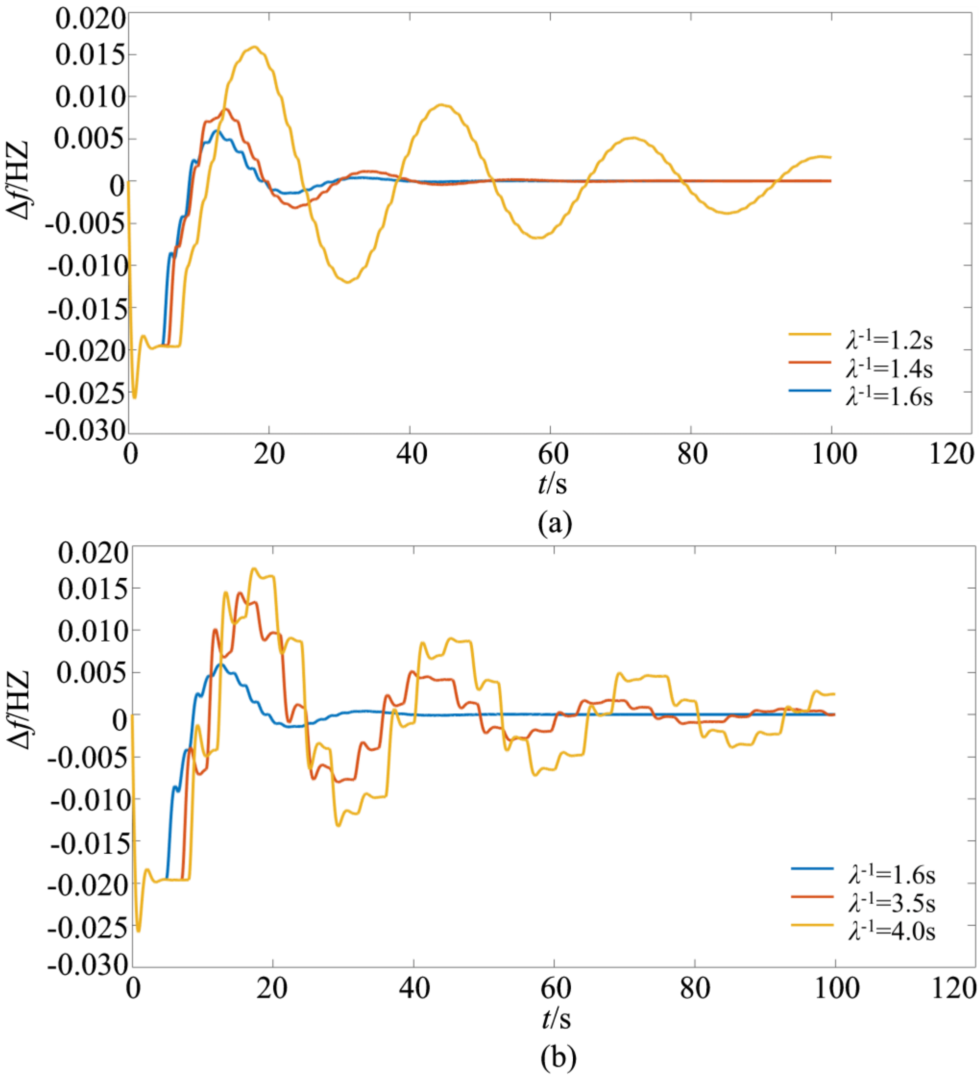

Figure 4.2 LFC performance of the proposed one-area LFC-AoI at different update frequencies. (a) Frequency deviation $\lambda^{-1}\leq$1.6s. (b) Frequency deviation $\lambda^{-1}\geq$1.6s.

This reveals that too high an update rate deteriorates LFC performance because of information queueing. Then it is observed from **Figure 4.2 (b)** that compared with λ^{-}

^{1}=1.6s, both λ^{-1}=3.5s and 4.0s lead to larger Δf fluctuations, and Δf with λ^{-1}=4.0s reaches the largest fluctuations relative to other two update frequencies. A close examination of **Figure 4.2 (b)** reveals that too low an update rate leads to worse LFC performance due to infrequently receiving information.

Then, we evaluate the LFC performance of the proposed PI-type controller based on AoI. Assume the allowable update frequency range from λ^{-1}=1.4s to λ^{-1}= 4.4s. By setting a=0, b=2.03, γ=20, and following Algorithm 1, the PI controller gains are given in **Table 4.2**.

Table 4.2 Designed PI-type controllers under different update rate.

λ^{-1}	1.4	1.6	1.8	2.0	2.2	2.4	2.6	2.8
K_I	-0.0112	-0.0234	-0.0325	-0.0365	-0.0411	-0.0422	-0.0402	-0.0429
K_P	-0.0044	-0.0092	-0.0127	-0.0143	-0.0161	-0.0165	-0.0158	-0.0168
λ^{-1}	3.0	3.2	3.4	3.6	3.8	4.0	4.2	4.4
K_I	-0.0418	-0.0431	-0.0435	-0.0430	-0.0437	-0.0421	-0.0419	-0.0432
K_P	-0.0164	-0.0170	-0.0171	-0.0169	-0.0172	-0.0167	-0.0166	-0.0171

When the system was subjected to random load disturbances, as shown in **Figure 4.4**, **Figure 4.3** compared the LFC performance with increasing update frequency under-designed PI controller in the one-area power system. Algorithm 1 designed the right PI controllers to optimal LFC with different update frequencies. However, when the update frequencies grow from λ^{-1}=1.4s to λ^{-1}= 4.4s, the LFC performance still first gets better, then get worse. And the update frequency at λ^{-1}= 2.0s is a critical point for optimal LFC performance.

To show the effectiveness of designing PI controllers based on AoI, frequency responses of a one-area power system for different update frequencies with the designed controller are illustrated in **Figure 4.3(b). Figure 4.3 (b)** verifies that the proposed PI controller with λ^{-1}=2.0s stabilizes the frequency deviation Δf quicker than the proposed PI controller with λ^{-1}=1.4s and the proposed PI controller with λ^{-1}=4.4s. This demonstrates the excellent ability of the proposed controller with the right update rate on LFC performance.

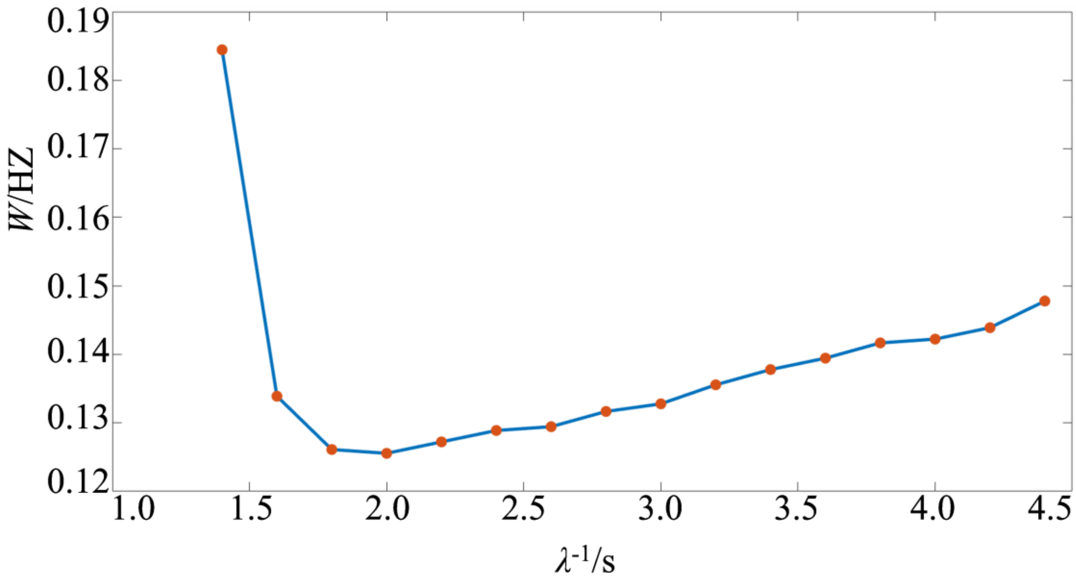

Figure 4.3 Performance of one-area LFC-AoI system under design PI controller for different update rates with random load disturbances.

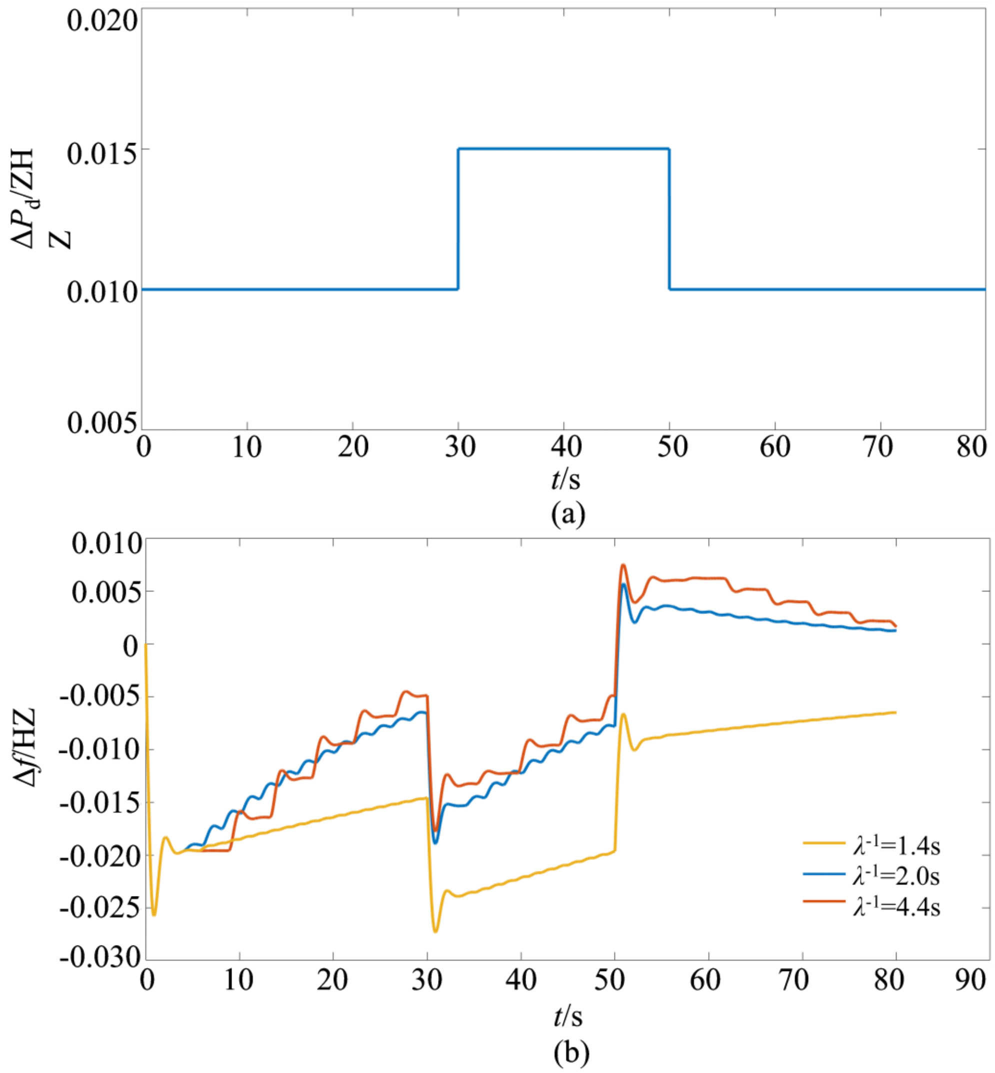

Figure 4.4 LFC performance of the proposed one-area LFC-AoI under design PI controller for random load disturbances. (a) Random load disturbances. (b) Frequency deviation.

4.4 Conclusion

Based on the multi-area LFC-AoI model in chapter 2, this chapter proposes an algorithm to design different PI controllers based on different update rates for a multi-area power system. This algorithm is different from the communication delay-based PI controller design, where the update rate decides the information freshness in the update process. Next, the fluctuation of LFC frequency is introduced as a performance metric to guide choosing the right update rate for a power system. One-area power systems have been undertaken to demonstrate show the necessity of considering the update rate effect on LFC performance, and the performance of LFC can be significantly optimized by the right update rate and design PI-type controller.

Chapter 5 Thesis conclusion and Future Work

Nowadays, modern load frequency control (LFC)systems employ an open communication system, which causes information staleness inevitably to arise. This issue can degrade the regulation performance of LFC and even threaten stability.

Chapter 2 introduces AoI into the power system to satisfy the increased need for LFC for real-time information updates. Previous research use communication delay to describe information packet freshness. And the information packet freshness is considered uncontrollable and cannot be influenced update rate. However, a muti-area LFC-AoI model is built to show that the update rate significantly influences the LFC performance. A high update rate leads to information queuing in front of the communication channel. On the other hand, a low update rate results in the controller infrequently receiving information. In addition, we create an AoI depending on the single-area LFC system stability criterion to find the maximum AoI as well as the update frequency range that allows the single-area LFC system performance to be stable. The case studies are based on a single-area LFC system, which shows the effect of update frequency and AoI on the stability of the LFC system and finds the maximum AoI and update frequency range that can make the performance of the LFC system stable.

Chapter 3 explains the difference between AoI and communication delay from object, definition, model, property, and margin. Delay only describes the staleness of each information packet, but AoI describes the whole information update process, which accurately presents the information freshness. The case demonstrates the AoI margin of the single-area LFC system and shows the information freshness impact on LFC performance. Simulation results also demonstrate that the AoI margin is larger than the delay margin and the large extent depends on the update rate.

Chapter 4 proposes an algorithm to design different PI controllers based on different update rates for a multi-area power system. This algorithm is different from the communication delay-based PI controller design, where the update rate decides the information freshness in the update process. Next, the fluctuation of LFC frequency is introduced as a performance metric to guide choosing the right update rate for a power system. One-area power systems have been undertaken to demonstrate show the necessity of considering the update rate effect on LFC performance, and the performance of LFC can be significantly optimized by the right update rate and design PI-type controller.

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