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Adaptive time-delay control of flexible loads in power systems facing accidental outages☆

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HIGHLIGHTS

- Increasing contingency reserve capacity by controlling flexible loads.
- Reconstructing a novel power system model under faulty condition.
- Modelling and integrating flexible loads into the reconstructed system model.
- Proposing adaptive time-delay control scheme to deal with communication delay.
- Decreasing maximum frequency deviation from −0.3276 Hz to −0.1337 Hz.

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ABSTRACT

The accidental outages of generating units are increasing in power systems, which can bring huge power shortage suddenly and lead to severe system oscillations. The secure operation of power systems sometimes cannot be guaranteed only by regulating traditional generating units, due to the rapid regulation requirement of making up for power shortage. To address this issue, this paper proposes using emergency demand response (DR) to provide contingency reserve capacities by adjusting the power consumption of flexible loads (FLs). Firstly, in order to analyze the dynamic regulation process of power systems in accidental outages, the power system model in faulty condition is reconstructed to obtain the regulation power from well-running generators. On this basis, FLs are modelled and integrated into the novel reconstructed power system model to be as an alternative method of making up for the fast regulation capacities. Considering that the inevitable communication time-delay probably leads to the slowdown of response speed and endangers the system security, an adaptive time-delay control (ATDC) scheme is proposed and integrated into the control process of aggregated FLs. In this manner, the regulation speed of FLs can be accelerated, the control precision of response capacities can be improved, and the power system frequency deviations caused by time-delay can be decreased. Finally, the proposed models and methods are verified by numerical studies. The results in the test system show that the frequency deviations can be decreased effectively from −0.3276 Hz to −0.1337 Hz in accidental outages by using the ATDC scheme of FLs.

1. Introduction

1.1. Challenges of accidental outages

The accidental outages of generating units are increasing in power systems around the world, which can bring huge power shortage suddenly, lead to severe system oscillations, and even result in large-scale blackouts. For example, two large generators in Hornsea and Little Barford disconnected from the main network in UK on August 9, 2019, which finally triggered around 1880 MW power output loss and affected more than one million users [1]. Similarly, on August 15, 2017, six gas generating units in Datan power plant shut down and caused serious blackout in Taiwan, China, which affected about 17 cities and 5.92 million customers [2]. In Australia, large-scale renewable

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Nomenclature

Acronyms

ATDC	adaptive time-delay control
DR	demand response
FLs	flexible loads
GTG	gas turbine generator
RSG	reheat steam generator

Variables and parameters

i	the i-th RSG (subscript)
j	the j-th GTG (subscript)
k	the k-th time interval (subscript)
l	the l-th user's FL (subscript)
n	the total number of RSGs
$\mathbf{N}$	the set of RSGs
m	the total number of GTGs
$\mathbf{M}$	the set of GTGs
Γ	set of shutdown RSGs
Ω	set of shutdown GTGs
α_{Ti}	ratio of the i-th RSG in the total power system capacity
α_{Gj}	ratio of the j-th GTG in the total power system capacity
α_{DR}	ratio of FLs' capacity in the total power system capacity
P_r	rated capacity of the power system
ΔP_{Ti}	regulation power from the i-th RSG
ΔP_{Gj}	regulation power from the j-th GTG
ΔP_G	the total regulation power of generators
$\Delta \widetilde{P}_G$	the remaining regulation power of generators
ΔP_D^{dev}	load power disturbance
R_{Ti}	speed droop gain of the i-th RSG
R_{Gj}	proportional gain of the j-th GTG
R_{DR}	proportional gain of FLs for participating in DR
K_{Ti}	integral gain of the i-th RSG
K_{Gj}	integral gain of the j-th GTG
T_{gi}	speed governor time constant of the i-th RSG
T_{ti}	steam turbine time constant of the i-th RSG
T_{ri}	steam turbine reheat time constant of the i-th RSG
F_{HPi}	high pressure turbine power fraction of the i-th RSG
c_{Gj},b_{Gj}	valve positioner constants of the j-th GTG
X_{Gj}	speed governor lead-time constant of the j-th GTG
Y_{Gj}	speed governor lag-time constant of the j-th GTG
T_{Fj}	fuel time constant of the j-th GTG
T_{CRj}	combustion reaction time delay of the j-th GTG
T_{CDj}	compressor discharge volume-time constant of the j-th GTG
Δf	power system frequency deviation
$\Delta f^{\min}$	minimum frequency deviation threshold for participating in DR
$\Delta f^{\max}$	maximum frequency deviation threshold for participating in DR
K_{PS}	power system gain constant
T_{PS}	power system time constant
$\Phi(s)$	closed-loop transfer function with regard to the load power disturbance
$\widetilde{\Phi}(s)$	closed-loop transfer function with regard to the load power disturbance after accidental outages
$\Psi(s)$	open-loop transfer function with regard to the load power disturbance
$\widetilde{\Psi}(s)$	open-loop transfer function with regard to the load power disturbance after accidental outages
p_{off}	switching-off probability of FLs
t_k^s	sending time of the system frequency deviation value
$t_{k,l}^r$	receiving time of the system frequency deviation value by the l-th FL
$t_{k,l}^d$	delay time from sending to receiving signals of the l-th FL
$\Delta f(t_k^s)$	actual value of system frequency deviations att_k^s
$\Delta f(t_{k,l}^r)$	actual value of system frequency deviations at$t_{k,l}^r$
$\Delta \widehat{f}\left(t_{k,l}^r\right)$	estimated value of system frequency deviations at$t_{k,l}^r$
$\Delta f_{FLs,l}(t_{k,l}^r)$	receiving value of system frequency deviations at$t_{k,l}^r$
$\Delta \widehat{f}_{FLs,l}\left(t_{k,l}^r\right)$	correction value of system frequency deviations at$t_{k,l}^r$

generating units dropped out from the power system on September 28, 2016, and resulted in 50 h blackout [3]. Obviously, compared with common load power disturbances, the accidental outages can cause larger fluctuations and more serious damages to the power system, mainly due to:

The generating unit capacities are generally larger than load disturbances, and can bring huge power shortage in a very short time. The regulation power capacities for maintaining the system balance are provided by generators [4]. The unit shutdown can further aggravate the shortage of system regulation capacities.

Although the remaining well-running generating units have enough regulation capacities in some networks, sometimes the generators cannot be regulated so rapidly to prevent the fast drop of power system frequencies, because of the generators' huge inertia [5].

Some previous studies have been done on accidental outages in power systems. In [6], the events, effects and origins of around thirty selected historic blackouts are analyzed to capture the common feature by utilizing the proposed coding framework. In this manner, the power system designers and security experts can rank the most imminent issues in the system to reduce the scale of blackouts. In [7], more than one hundred representative historic blackouts are performed to analyze the principal threats to the secure operation of power systems. In [8], the resilience of electrical power distribution systems is approximated by the duration of accidental outages, which verifies that the interaction between infrastructure and the biophysical environment have significant effects on the system's outage duration. In [9], the impact of human operating errors in power systems are considered to investigate the plant power outages and influences on system reliability. However, the above research mainly focuses on the causes and prevention methods of accidental outages, while the methods for decreasing the impact of accidental outages on power systems are not studied.

Besides, in [10], the hybrid-neuro-fuzzy method is proposed to solve the automatic generation control problem in a restructured power system, which is evaluated and compared with hybrid particle swarm optimization, real coded genetic algorithm, and artificial neural network controllers to illustrate its robust performance. In [11], the redox flow batteries is investigated and utilized in automatic generation control of restructured power systems, which is also extended to a two-area multi-source power systems with thermal and hydro generating units. However, the studies in [10] and [11] mainly focus on the electrical power market, while not the control methods of regulation resources under accidental outages.

In [12], the dynamical and probabilistic approaches are utilized to study the blackout of transmission grids. In [13], the concept of generalized congestions is proposed based on the realistic power systems of India, in which the strong smart grid is regarded as a positive scheme for insuring future energy security. Indeed, the studies in [12] and [13] can improve the power systems' security and decrease the blackouts by updating the transmission systems. Nevertheless, this method will raise the construction cost of power systems, and still cannot avoid the accidental outages caused by generating units' shutdown.

To sum up, the previous studies on restructured power systems mainly concentrated in causes and prevention methods of accidental outages by analyzing environment effects, finding the most imminent issues, and updating the transmission network. However, the control methods of regulation resources for decreasing the impact of accidental outages on power systems need to be further studied.

1.2. Solutions from demand side resources

To address the accidental outages, the progressed information and communication technologies provide an alternative approach from demand side [14], which is called demand response (DR) [15]. DR is providing regulation services for power systems by adjusting the power consumption of flexible loads (FLs) [16], such as electric vehicles [17], air conditioners [18], and water heaters [19]. In [20], electric vehicles are aggregated as an efficient power plant to provide active power regulations services for wind farms. It proves that the electric vehicles can effectively decrease the generators' output variations by participating in DR. In [21], aggregated air conditioners are regarded as FLs to provide operating reserve for power systems, which can be equivalent to traditional generating units to decrease power system frequency deviations when facing power disturbances [22]. Besides, the thermostatic loads [23], smart buildings [24], and electric vehicles [25] are controlled to provide frequency regulation services for power systems, in which the impacts on customers' comfort are proved to be little [26].

Apart from above studies, quite a few actual investigations in DR have also been carried out. For example, more than 1500 residential customers in New York and Texas in the U.S. are surveyed toward DR projects [27]. The results show that most of customers have interests to participate in DR through reward payments. In [28], customers' FLs are proven to be effective to provide balancing resources for power systems and district heating systems. Besides, based on the Internet of Things technologies, a plug-and-play learning framework is proposed and validated in a building to provide reliable thermal model for implementing DR [29]. In the demonstration project in Ota City, Japan [30], FLs are utilized for voltage regulation in power distribution systems. In addition, the multi-step formulated convolutional neural network [31] and load profiling techniques [32] have been employed to illustrate the huge regulation potential and great value of DR.

To summarize, DR has been studied and validated to be effective for providing regulation services to power systems [33]. However, most of the previous studies focus on the modelling and control methods of FLs to deal with the load power disturbances. That is to say, the power system structure (including the number of generating units, transmission and distribution networks) remains unchanged. DR is only regarded as a useful supplement to power systems, instead of replacing generating units to be as the primary resources [34].

When the accidental outages occur in power systems, the huge power shortage will arise in a very short time. It can lead to the fast drop of power system frequencies, and probably result in large-scale blackouts. Therefore, in order to avoid these serious accidents, the generating units and FLs should be controlled and regulated rapidly to make up for the power shortage as soon as possible. However, according to actual tests, the communication time-delay and operational time-delay are inevitable in power systems, which generally distribute randomly in some ranges [35]. The time-delay can slow down the FLs' response speed, and reduce the FLs' regulation effect. Moreover, it has been proven that the time-delay can lead to significant control errors of FLs' capacities, and even bring more additional oscillations to power systems [36]. Besides, the time-delay in the control process of FLs can lead to more influences on customers' comfort, shorten the service life of appliances which participate in DR, and affect the normal regulation of traditional generating units. More seriously, the time-delay in the control process of FLs can cause the power system to diverge and become an unstable system, especially in the condition of large-scale FLs with complex communication networks [36]. In other words, when the load disturbances or accidental outages occur, an unstable system cannot restore balance due to the time-delay. At this moment, FLs' regulation has the opposite effect for maintaining the system stability. Therefore, the time-delay problem during the control process of FLs has to be paid more attention to guarantee FLs' positive effect for power systems.

In [37] and [38], the single-area power system model and two-area power system model are developed, respectively, in which the DR control loop and communication time-delay are considered. However, the studies in [37] and [38] only analyze the stability margin of power systems under the influence of time-delay. The compensation methods for correcting the errors brought by time-delay is not studied. In [39], the stochastic predictive controller and *Kalman* filter-based state estimation techniques are deployed to reduce the effects of communication delays, while the algorithm is designed specifically for thermostatically controlled loads, rather than general FLs. This algorithm can forecast the indoor temperature and the power consumption of thermostatically controlled loads, so as to take action to control these loads in advance. In [40], the fuzzy-PI-based supervisory controller is introduced as a coordinator to avoid large overshoots or undershoots of system frequencies as a result of communication delays. However, this controller is only for dealing with tie-line power flows in multi-area power systems, where the accidental outages are not studied. Besides, the fuzzy-PI-based supervisory controller has to regulate traditional generating units repeatedly to suppress the fluctuations brought by FLs, which is impracticable in accidental outages.

In summary, the control method of FLs considering time-delay effects in accidental outages has not been fully studied, while the frequent generating unit shutdown accidents in actual power systems require us to deal with this problem as soon as possible.

1.3. Contributions

To address the above issues, this paper proposes an adaptive time-delay control (ATDC) strategy of FLs in power systems facing accidental outages, so as to accelerate response speed, improve response capacities' control precision, and decrease system frequency deviations caused by time-delay. The proposed models and methods can provide important references for developing DR in smart grid paradigm. The main contributions of this paper can be summarized as follows:

- A typical power system model with reheat steam generators and gas turbine generators are developed. On this basis, the power system model is reconstructed to be as a novel system model after accidental outages. In this manner, the dynamic regulation process from remaining well-running generators can be studied.
- Flexible loads are modelled and integrated into this novel reconstructed power system model in accidental outages, to be as an alternative method of making up for the fast regulation capacities. Besides, a stochastic decision control strategy is developed for achieving the smoothness regulation of large-scale aggregated flexible loads.
- The communication time-delay in the control process of flexible loads is modelled to study the harmful impacts on the reconstructed power system in accidental outages. To address this issue, an adaptive time-delay control strategy of flexible loads is proposed to accelerate response speed, improve the control precision of response capacities, and decrease system frequency deviations.

The remainder of this paper is organized as follows. Section 2 presents the modelling method of the reconstructed power system in accidental outages, where the regulation power is from traditional generating units and the disturbance power is from broken-down generators. Then, modelling and control methods of FLs are presented and integrated into power systems in Section 3. On this basis, the time-delay model during FLs' control process is developed in Section 4, where the ATDC scheme is proposed to correct the errors brought by communication time-delay. Section 5 verifies the effectiveness of the proposed models and methods using numerical studies. Finally, Section 6 and Section 7 concludes this paper and the future work, respectively.

2. Modelling of power systems in accidental outages

2.1. Transfer function model of power systems

Fig. 1(a) shows a typical power system model [2,41]. It is assumed that the power system includes reheat steam generators (RSGs) and gas turbine generators (GTGs), which are the main generator types in power systems around the world [42]. As for a power system in the balance state, the disturbance load power ΔP_D^{dev} can cause system frequency deviations Δf. Then, the generators in the system will regulate their power output based on the frequency deviations, including the regulation power from RSGs ΔP_{Ti} and GTGs ΔP_{Gj}.

The regulation power from RSGs and GTGs will increase until the system recover its balance. As shown in Fig. 1(a), ΔP_G is the total regulation power provided by all the generators in the system, which can be calculated by

$$\Delta P_G(s) = \sum_{i=1}^{n} \Delta P_{Ti}(s) + \sum_{j=1}^{m} \Delta P_{Gj}(s) \tag{1}$$

where ΔP_{Ti} and ΔP_{Gj} are the regulation power from the i-th RSG and j-th GTG, respectively. n and m are the total number of RSGs and GTGs, respectively. Denoting $i \in \mathbf{N}$ and $j \in \mathbf{M}$ as the set of RSGs and GTGs, respectively, which can be expressed as $\mathbf{N} = \{1, 2, ..., n\}$ and $\mathbf{M} = \{1, 2, ..., m\}$.

Based on the transfer function model in Fig. 1(a), the regulation power of RSG can be described as

$$\Delta P_{Ti}(s) = -\alpha_{Ti}\cdot\left(\frac{1}{R_{Ti}} + \frac{K_{Ti}}{s}\right)\cdot\frac{1}{1 + sT_{gi}}\cdot\frac{1 + sF_{HPi}T_{ri}}{(1 + sT_{ti})(1 + sT_{ri})}\cdot\Delta f \tag{2}$$

where α_{Ti} is the ratio of the i-th RSG in the total power system capacity. R_{Ti} and K_{Ti} are the speed droop gain and integral gain, respectively. T_{gi}, T_{ti}, and T_{ri} are the speed governor time constant, steam turbine time constant, and the steam turbine reheat time constant, respectively. F_{HPi} is the high pressure turbine power fraction.

Similarly, the regulation power of GTG can be described as

$$\Delta P_{Gj}(s) = -\alpha_{Gj}\cdot\left(\frac{1}{R_{Gj}} + \frac{K_{Gj}}{s}\right)\cdot\frac{1}{c_{Gj} + sb_{Gj}}\cdot\frac{1 + sX_{Gj}}{1 + sY_{Gj}}\cdot\frac{1 + sT_{CRj}}{(1 + sT_{Fj})(1 + sT_{CDj})}\cdot\Delta f \tag{3}$$

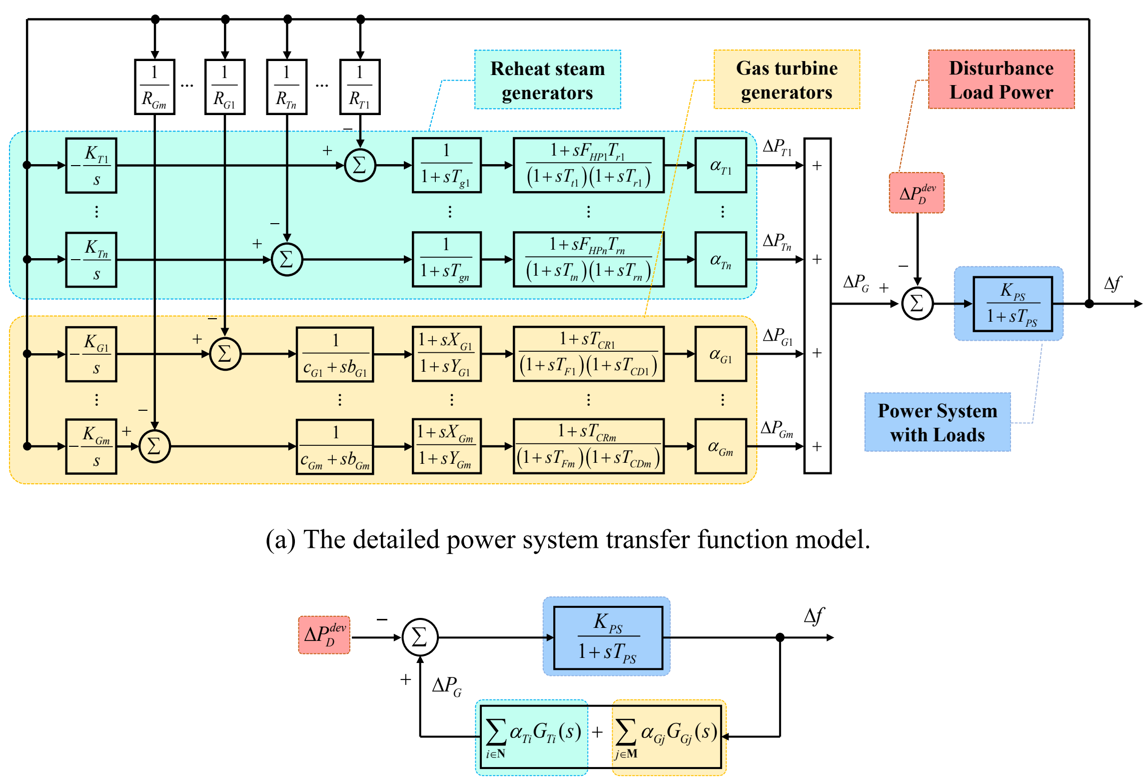
where α_{Gj} is the ratio of the j-th GTG in the total power system capacity. R_{Gj} and K_{Gj} are the proportional and integral gains, respectively. c_{Gj} and b_{Gj} are the valve positioner constants. X_{Gj} and Y_{Gj} are the speed governor lead- and lag-time constants, respectively. T_{Fj}, T_{CRj}, and T_{CDj} are the fuel time constant, combustion reaction time delay, and compressor discharge volume-time constant, respectively.

Therefore, the dynamic regulation process of the power system can be expressed as

$$\Delta f(s) = \frac{K_{PS}}{1 + sT_{PS}}(\Delta P_G(s) - \Delta P_D^{dev}(s)) \tag{4}$$

where K_{PS} and T_{PS} are the power system's gain and time constants, respectively.

In order to simplify the dynamic analysis process, the power system transfer function model in Fig. 1(a), can be converted into a typical control loop, as shown in Fig. 1(b). The power system is the controlled object. The load power ΔP_D^{dev} is the control loop's external disturbance.



(a) The detailed power system transfer function model.

(b) The simplified power system transfer function model.

Fig. 1. The transfer function model of the power system with reheat steam generators and gas turbine generators, when facing random load power disturbances and system frequency deviations.

The system frequency deviation Δf is the control objective. The generators constitute the feedback loop. $M(s)$, $G_{Ti}(s)$, and $G_{Gj}(s)$ in Fig. 1(b) represent aggregated transfer functions, which are

$$M(s) = \frac{K_{PS}}{1 + sT_{PS}} \tag{5}$$

$$G_{Ti}(s) = -\left(\frac{1}{R_{Ti}} + \frac{K_{Ti}}{s}\right)\cdot\frac{1}{1+sT_{gi}}\cdot\frac{1+sF_{HPi}T_{ri}}{(1+sT_{ti})(1+sT_{ri})} \tag{6}$$

$$G_{Gj}(s) = -\left(\frac{1}{R_{Gj}} + \frac{K_{Gj}}{s}\right)\cdot\frac{1}{c_{Gj}+sb_{Gj}}\cdot\frac{1+sX_{Gj}}{1+sY_{Gj}}\cdot\frac{1+sT_{CRj}}{(1+sT_{Fj})(1+sT_{CDj})} \tag{7}$$

Therefore, the power system transfer function model in Fig. 1(b) composes a closed-loop control system. The closed-loop transfer function with regard to the load power disturbance can be described as

$$\Phi(s) = \frac{\Delta f(s)}{\Delta P_D^{dev}(s)} = \frac{-M(s)}{1 - \underbrace{M(s)\left(\sum_{i=1}^{n}\alpha_{Ti}G_{Ti}(s) + \sum_{j=1}^{m}\alpha_{Gj}G_{Gj}(s)\right)}_{\Psi(s)}} \tag{8}$$

where $\Psi(s)$ is the corresponding open-loop transfer function.

2.2. Reconstructed transfer function model of power systems

As shown in Fig. 1(b), the load power disturbances are regarded as control loop's external disturbances, which do not change the power system structure, including the number of generating units, transmission and distribution networks. In other words, the load power disturbances cannot affect the structure of the control loop.

However, as for the accidental outages, the feedback loop of the control system will be changed, because the number of well-running generators becomes less. Therefore, the remaining regulation power can be expressed as

$$\Delta\widetilde{P}_G(s) = \sum_{i\in\mathbf{N}, i\notin\Gamma}\alpha_{Ti}G_{Ti}(s) + \sum_{j\in\mathbf{M}, j\notin\Omega}\alpha_{Gj}G_{Gj}(s) \tag{9}$$

where Γ and Ω are the sets of shutdown RSGs and GTGs, respectively.

The outages refer to the change of operating states of generating units from the normal operation state to shutdown state, which can lead to power disturbances to the system. Three typical outages are analyzed here, as shown in Fig. 2.

Fig. 2(a) is the accidental outage, where the generation power of the generating unit drops from the normal operation state to zero almost instantaneously. Fig. 2(b) refers to the slow-changing outages, where the faults occur at time t_1 and stop to generate power completely after some duration time. The main difference of Fig. 2(a) and (b) is the shutdown duration time of generators. Moreover, Fig. 2(c) refers to the lagging outages, i.e., the generators can continue provide electricity during the initial period of time. For example, the gas turbine generators can operate normally at first, when the gas well or gas storage devices fail. Because the gas turbine generators can use the stored gas in pipelines for some time.

To summarize, the accidental outages in Fig. 2(a) can bring the most serious harm to the stable operation of power systems, which is exactly what this paper focuses on. Due to the almost instantaneous change of operating power in Fig. 2(a), the accidental outage can be regarded as a step function, and expressed as

$$\Delta P_D^{dev}(s) = \frac{\left|\sum_{i\in\Gamma}\alpha_{Ti}G_{Ti}(s)\right|}{s} + \frac{\left|\sum_{j\in\Omega}\alpha_{Gj}G_{Gj}(s)\right|}{s} \tag{10}$$

In order to analyze the dynamic performances of the novel power system model after accidental outages, the outage capacities of generators can be regarded as increased load power. Therefore, the reconstructed power system model after accidental outages can be illustrated as Fig. 3.

On this basis, the novel closed-loop transfer function with regard to accidental outages can be described as

$$\widetilde{\Phi}(s) = \frac{\Delta f(s)}{\Delta P_D^{dev}(s)} = \frac{-M(s)}{1 - \underbrace{M(s)\left(\sum_{i\in\mathbf{N}, i\notin\Gamma}\alpha_{Ti}G_{Ti}(s) + \sum_{j\in\mathbf{M}, j\notin\Omega}\alpha_{Gj}G_{Gj}(s)\right)}_{\widetilde{\Psi}(s)}} \tag{11}$$

where $\widetilde{\Psi}(s)$ is the corresponding open-loop transfer function of the reconstructed power system.

3. Modelling and control of flexible loads

3.1. Modelling of flexible loads

To address the accidental outages, the progressed information and communication technologies provide an alternative regulation approach by controlling the power consumption of flexible loads (FLs) [14]. In order to decrease the impact on users' comfort during control process of loads, thermostatically controlled loads (TCLs) which can store energy are selected in this paper, such as water heaters, heat pumps, and air conditioners [15]. TCLs account for a large share of the total electricity consumption, for example, statistical data show that air conditioners occupy around 40% of the total loads [43]. Therefore, TCLs have huge regulation potential, and can be switched off temporarily when the regulation capacity is need in power systems.

It is assumed that the operating state and operating power of available FLs are expressed as $\mathbf{S}_{FLs} = [S_{D,1}(t), S_{D,2}(t), ..., S_{D,l}(t)]^T$ and $\mathbf{P}_{FLs} = [P_{D,1}, P_{D,2}, ..., P_{D,l}]^T$, respectively. The operating state of FLs has two values, i.e., $S_{D,l}(t) \in \{0, 1\}$, where 0 represent off-state and 1 is on-state. Therefore, the total power of FLs can be calculated as

$$P_{FLs} = P_{FLs}^T S_{FLs} = \sum_{i=1}^{l} P_{D,i}S_{D,i}(t) \tag{12}$$

When the power system frequency deviations occur, some FLs will be switched from original on-state to off-state. With the increasing of frequency deviations, more FLs will be switched off to provide regulation services for power systems, as shown in Fig. 4(a).

Therefore, the regulation power from FLs can be calculated as

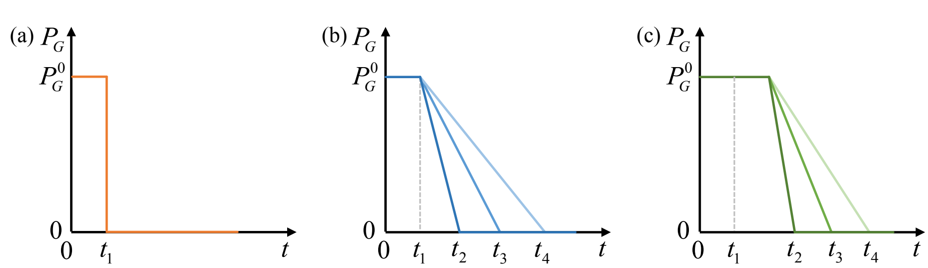


Fig. 2. The distinctions among three typical outages in power systems. (a) The accidental outage. (b) The slow-changing outages. (c) The lagging outages.

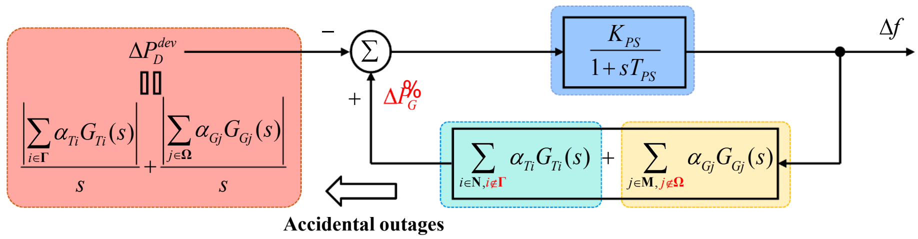


Fig. 3. The reconstructed transfer function model of the power system with reheat steam generators and gas turbine generators after accidental outages of generating units.

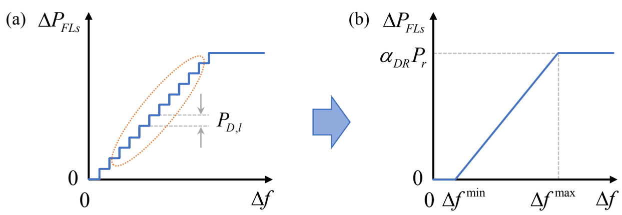


Fig. 4. The regulation power provided by flexible loads utilizing the on-off control method. (a) The micro curve of the regulation power provided by each flexible load. (b) The macro curve of the regulation power provided by large-scale flexible loads.

$$\Delta P_{FLs} = \sum_{i=1}^{l} P_{D,i}(S_{D,i}(t) - S_{D,i}(t)) \tag{13}$$

where $\widetilde{S}_{D,i}(t)$ is the operating state of FLs after regulation.

Considering the large-scale FLs in realistic power systems, the step-curve in Fig. 4(a) can be regarded as smooth curve, as shown in Fig. 4(b). In order to avoid FLs' frequent actions and impact users' comfort, the minimum value of frequency deviation $\Delta f^{\min}$ is set as the threshold for participating in DR. In other words, when the system frequency deviations are less than $\Delta f^{\min}$, FLs will not take action. The power system is regulated to recover balance only by well-running generating units.

When the system frequency deviations increase larger than the minimum threshold, more FLs will participate in DR with the increase of deviations. Besides, considering the limitation of the total number of FLs, all the FLs' regulation capacities will be activated if the frequency deviation exceeds the maximum threshold $\Delta f^{\max}$. Therefore, the control objective of aggregated FLs' regulation capacities can be expressed as

$$\Delta P_{FLs} = \begin{cases} 0, & \Delta f \leqslant \Delta f^{\min} \\ \frac{1}{R_{DR}}(\Delta f - \Delta f^{\min}), & \Delta f^{\min} < \Delta f \leqslant \Delta f^{\max} \\ \alpha_{DR}P_r, & \Delta f > \Delta f^{\max} \end{cases} \tag{14}$$

where R_{DR} is the proportional gain of FLs for participating in DR with regard to system frequency deviations. P_r is the system's rated capacities. α_{DR} is the ratio of total FLs' capacities as for P_r. Based on the equation (14), the proportional gain R_{DR} can be calculated as

$$R_{DR} = \frac{\Delta f^{\max} - \Delta f^{\min}}{\alpha_{DR}P_r} \tag{15}$$

3.2. Control of flexible loads

Based on the modelling of FLs in Section 3.1 and the reconstructed power system model facing accidental outages in Section 2.2, FLs can be further integrated into power systems for improving the dynamic performances and decreasing the impact of accidental outages.

As shown in Fig. 5, the power system frequency deviations are detected by the aggregator of FLs, and then transmitted to each user to adjust their power consumptions. In order to achieve the control objective in equation (14), a stochastic decision method is utilized here [44]. Each FL is set to be switched off at a probability p_{off}, which can be expressed as

$$p_{off} = \frac{\Delta P_{FLs}}{\alpha_{DR}P_r} \tag{16}$$

As for one FL's controller, it generates a number randomly from 0 to 1. If the number is less than the probability p_{off}, the FL will be switched off. By contrast, if the number is lager than the probability p_{off}, the FL

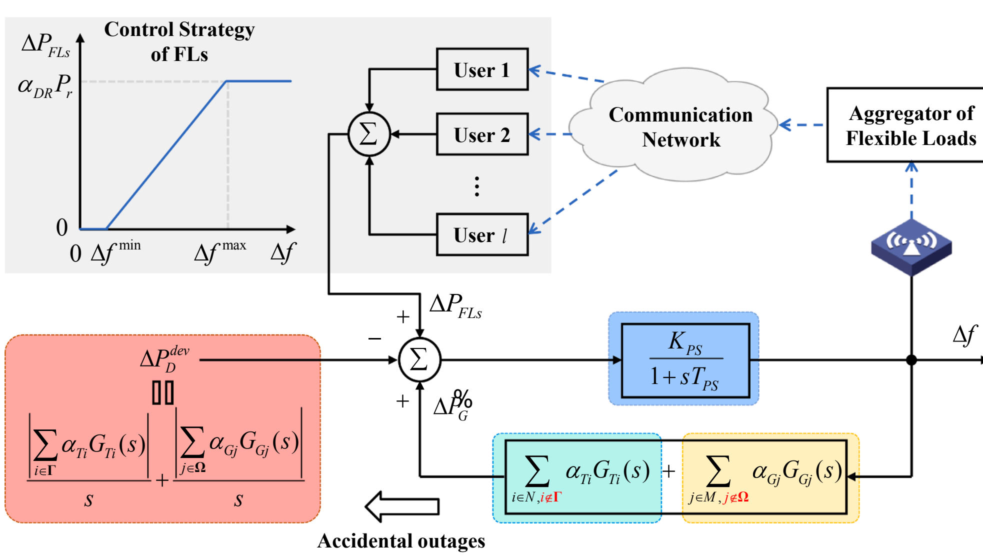


Fig. 5. The reconstructed transfer function model of the power system with reheat steam generators and gas turbine generators after accidental outages of generating units, considering the frequency regulation of flexible loads.

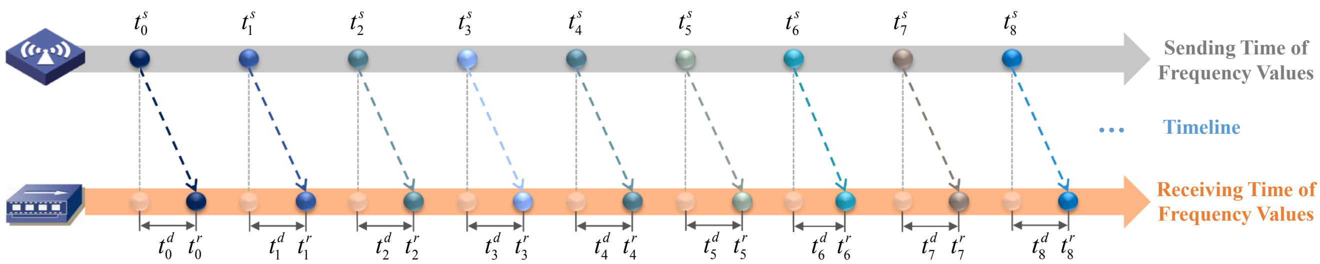


Fig. 6. Communication delay in the control process of flexible loads.

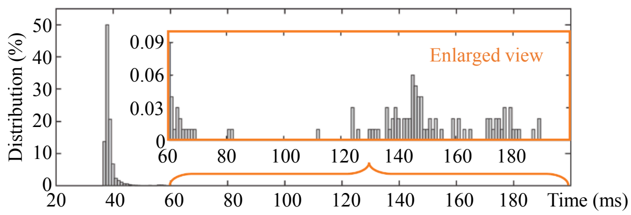


Fig. 7. Distribution of communication delay in power systems [35].

will remain on state. The stochastic decision criteria can be expressed as

$$\begin{cases} \text{if } U(0,1) \leqslant p_{off}, \text{ switch off} \\ \text{if } U(0,1) > p_{off}, \text{ remain on} \end{cases} \tag{17}$$

Based on the reconstructed power system model in accidental outages (i.e., equations (9)–(11)) and the FLs' model (i.e., equations (12)–(17)), the power system's dynamic process can be expressed as

$$\Delta f(s) = \frac{K_{PS}}{1+sT_{PS}}(\Delta\widetilde{P}_G(s) + \Delta P_{FLs} - \Delta P_D^{dev}(s))$$

$$= \frac{K_{PS}}{1+sT_{PS}}\left[\sum_{i\in\mathbf{N}, i\notin\Gamma} \alpha_{Ti}G_{Ti}(s) + \sum_{j\in\mathbf{M}, j\notin\Omega} \alpha_{Gj}G_{Gj}(s) + \Delta P_{FLs} - \left|\sum_{i\in\Gamma}\alpha_{Ti}G_{Ti}(s)\right| \Big/ s - \left|\sum_{j\in\Omega}\alpha_{Gj}G_{Gj}(s)\right| \Big/ s\right] \tag{18}$$

4. Communication delay and adaptive control method

4.1. Communication delay during the control process

In the above models, the FLs are controlled in ideal conditions, i.e., power system frequency deviations can be detected and transmitted to each user instantaneously. However, in reality, communication time-delay and operational time-delay of FLs are inevitable in power systems, especially for large-scale FLs with complex communication networks. It is assumed that the sampling density of the system frequency is t_k^s ($k = 1, 2, ..., K$), and the corresponding detected frequency deviation is $\Delta f(t_k^s)$. The deviation value is sent to and received by each FL's controller at time $t_{k,l}^r$ ($k = 1, 2, ..., K$; $l = 1, 2, ..., L$), as shown in Fig. 6.

The detected frequency deviation value $\Delta f(t_k^s)$ is transmitted with time delay, while the value remains unchanged. The transmission process can be expressed as

$$t_{k,l}^r = t_k^s + t_{k,l}^d \tag{19}$$

$$\Delta f_{FLs,l}(t_{k,l}^r) = \Delta f(t_k^s) \tag{20}$$

where $t_{k,l}^r$ is the time when the l - th FL receives the frequency value after communication delay time $t_{k,l}^d$. The $\Delta f_{FLs,l}(t_{k,l}^r)$ is the received frequency deviation value of the l - th FL at time $t_{k,l}^r$.

Based on the actual test in Silin, Guizhou, China [35], the communication delay is not a fixed value, while it is randomly distributed, as shown in Fig. 7. Therefore, the delay time varies among FL individuals each time. Considering the fast drop of system frequency in

Table 1
Parameters of RSGs and GTGs [2,45].

Parameters	Values	Parameters	Values
R_{Ti}	0.05	c_{Gj}	1.00
K_{Ti}	0.10 s $^{-1}$	b_{Gj}	0.05 s
T_{gi}	0.20 s	X_{Gj}	0.60 s
T_{ti}	0.30 s	Y_{Gj}	1.00 s
T_{ri}	10.00 s	T_{Fj}	0.23 s
F_{HPi}	0.30	T_{CRj}	0.01 s
R_{Gj}	0.05	T_{CDj}	0.20 s
K_{Gj}	0.10 s $^{-1}$	K_{PS}	1.1493
α_{Ti}	0.10	T_{PS}	11.49 s
α_{Gj}	0.06	R_{DR}	0.20

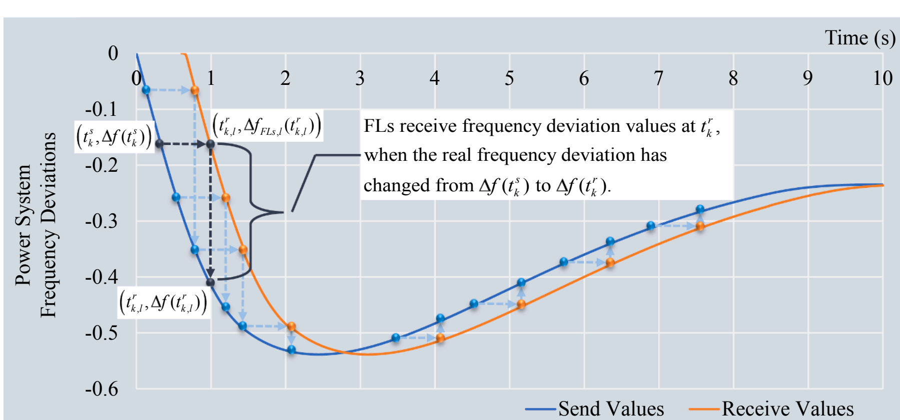


Fig. 8. The sent and received system frequency deviations for flexible loads when participating in power systems' regulation services.

Table 2
Case studies and scenarios.

Time-delay	Scenarios							
	GTG shutdown accident				RSG shutdown accident			
	FL capacity							
	0 MW (0%)	160 MW (2%)	320 MW (4%)	480 MW (6%)	0 MW (0%)	160 MW (2%)	320 MW (4%)	480 MW (6%)
0 ms	SG00	SG01	SG02	SG03	SR00	SR01	SR02	SR03
50 ms	N/A	SG11	SG12	SG13	N/A	SR11	SR12	SR13
200 ms	N/A	SG21	SG22	SG23	N/A	SR21	SR22	SR23
500 ms	N/A	SG31	SG32	SG33	N/A	SR31	SR32	SR33

1. The ATDC scheme can be used in the shadow areas, i.e., SG11 ~ SG33, SR11 ~ SR33.
2. “N/A” is “Not applicable”.

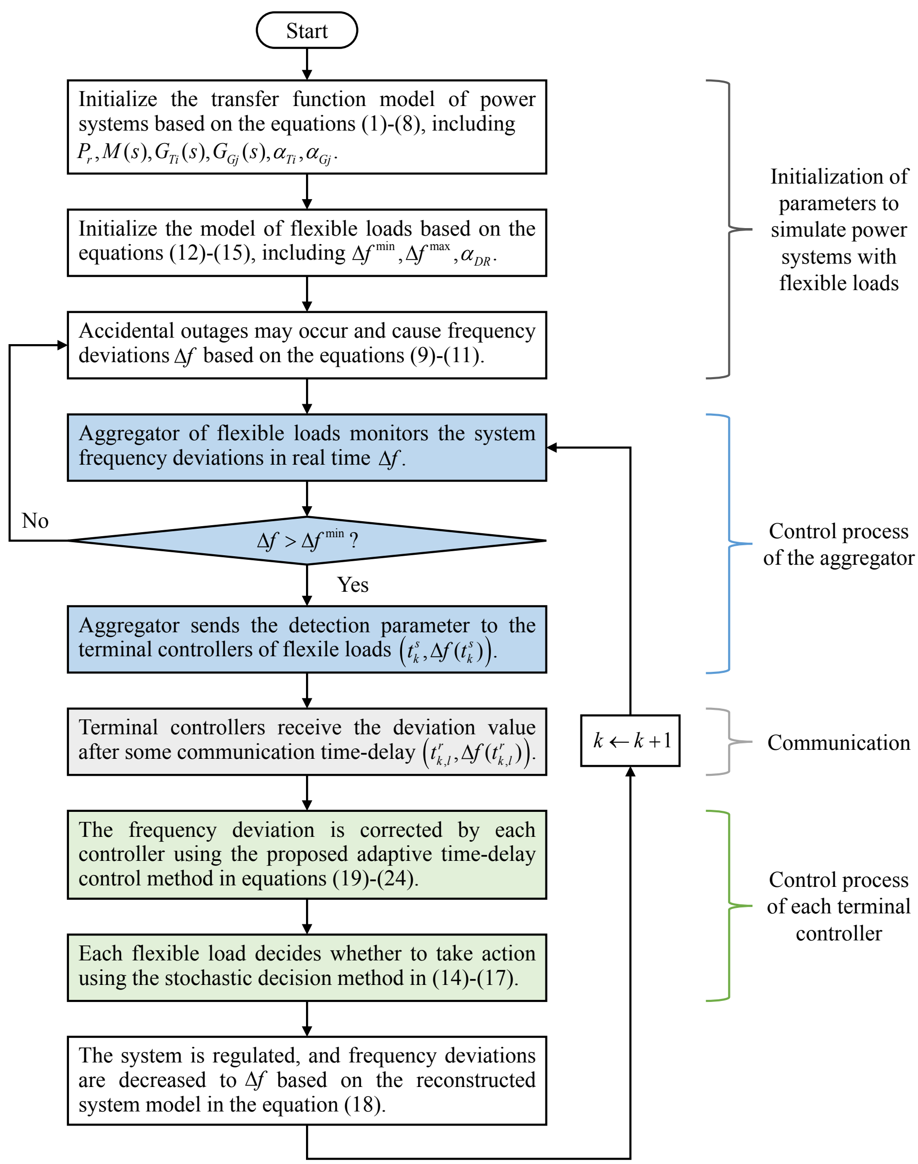


Fig. 9. The implementation procedure of the adaptive time-delay control of flexible loads.

accidental outages, the communication delay has to be taken into account to improve the control prevision of FLs. To address this issue, an adaptive time-delay control (ATDC) method is proposed in the next subsection.

4.2. Adaptive time-delay control method

As shown in Fig. 8, when the l - th FL receives the frequency deviation value at $t_{k,l}^r$, the actual deviation value has changed from $\Delta f_{FLs,l}(t_{k,l}^r)$ to $\Delta f(t_{k,l}^r)$. However, as for the FL, it cannot know this actual value. If the FL takes action based on $\Delta f_{FLs,l}(t_{k,l}^r)$, the large-scale FLs' DR

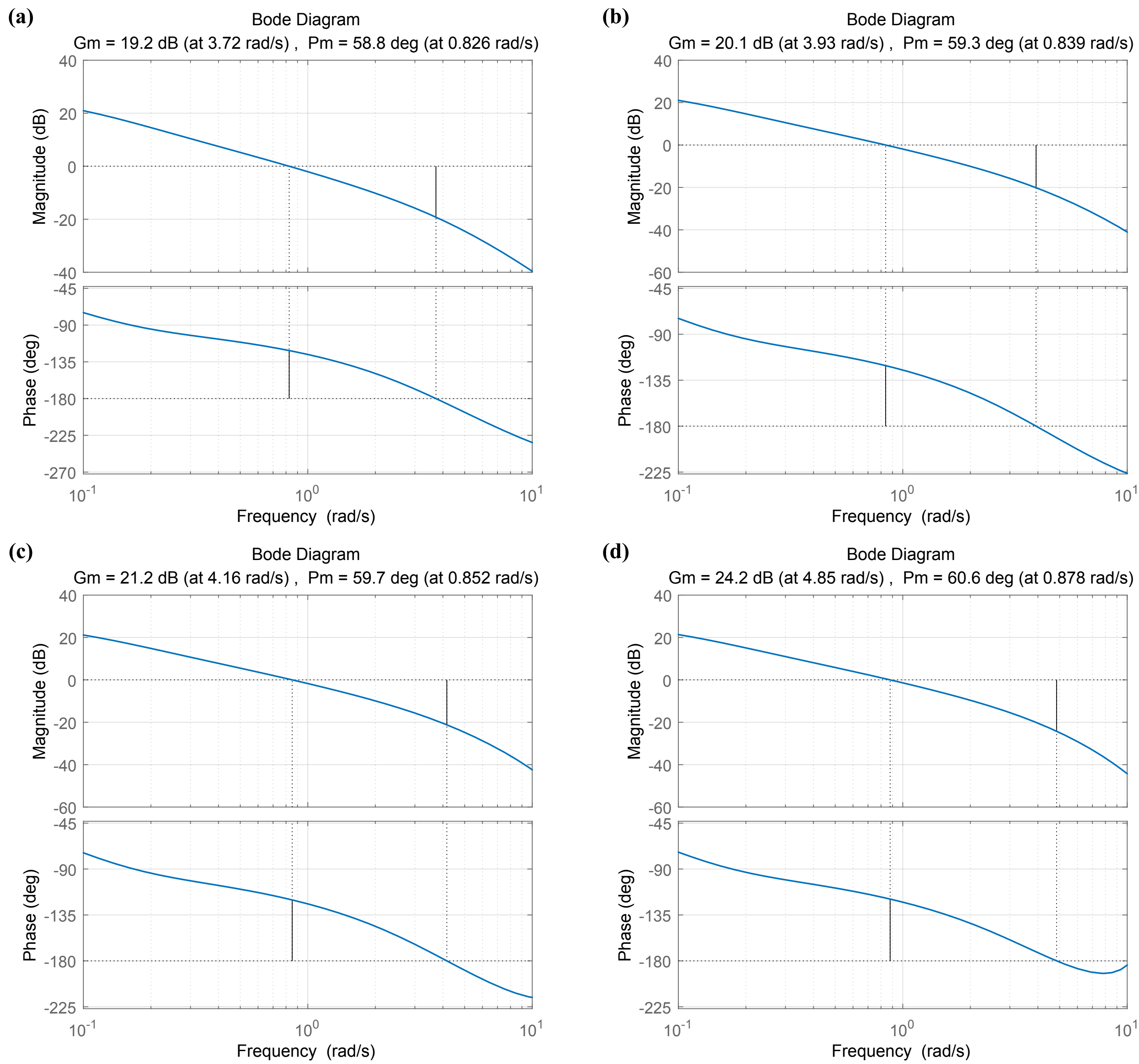


Fig. 10. The Bode plot comparisons of the power system with and without FLs when the communication delay is not considered during the control process of FLs. (a) SG00, without FLs; (b) SG01, with 160 MW FLs for providing regulation services; (c) SG02, with 320 MW FLs for providing regulation services; (d) SG03, with 480 MW FLs for providing regulation services.

probably cause severe power systems' oscillations. More seriously, with the increase of possible communication delays, FLs have negative impacts on the stability of power systems and can cause the system to be divergent [36].

Therefore, our objective of the proposed ATDC scheme is to estimate the actual frequency deviation value Δf at time $t^r_{k,l}$, based on the received value $\Delta f_{FLs,l}(t^r_{k,l})$. Admittedly, the simplest and direct manner is to improve the communication infrastructure to decrease the delay time, while this way is with high cost for massive FLs and reduces the practicality of DR. The objective of ATDC in each FL's controller is expressed as

$$\Delta f(t^r_{k,l}) \leftarrow \Delta f_{FLs,l}(t^r_{k,l}) \tag{21}$$

It is assumed that the estimated frequency deviation value is $\widehat{\Delta f}(t^r_{k,l})$, which is calculated by

$$\widehat{\Delta f}(t^r_{k,l}) = \Delta f_{FLs,l}(t^r_{k,l}) + \widehat{\Delta f_{FLs,l}}(t^r_{k,l}) \tag{22}$$

where $\widehat{\Delta f_{FLs,l}}(t^r_{k,l})$ is the correction value. Considering the data storage capacity of each FL's terminal controller, a large amount of historical data probably are not available. Therefore, the proposed ATDC method is designed to only need the adjacent data, and the correction value is obtained from

$$\begin{aligned}\widehat{\Delta f_{FLs,l}}(t^r_{k,l}) &= \frac{\Delta f(t^s_k) - \Delta f(t^s_{k-1})}{t^s_k - t^s_{k-1}}(t^r_{k,l} - t^s_k)\\ &= \frac{\Delta f_{FLs,l}(t^r_{k,l}) - \Delta f_{FLs,l}(t^r_{k-1,l})}{t^s_k - t^s_{k-1}}(t^r_{k,l} - t^s_k)\end{aligned} \tag{23}$$

Based on the equations (20)–(23), the estimated frequency

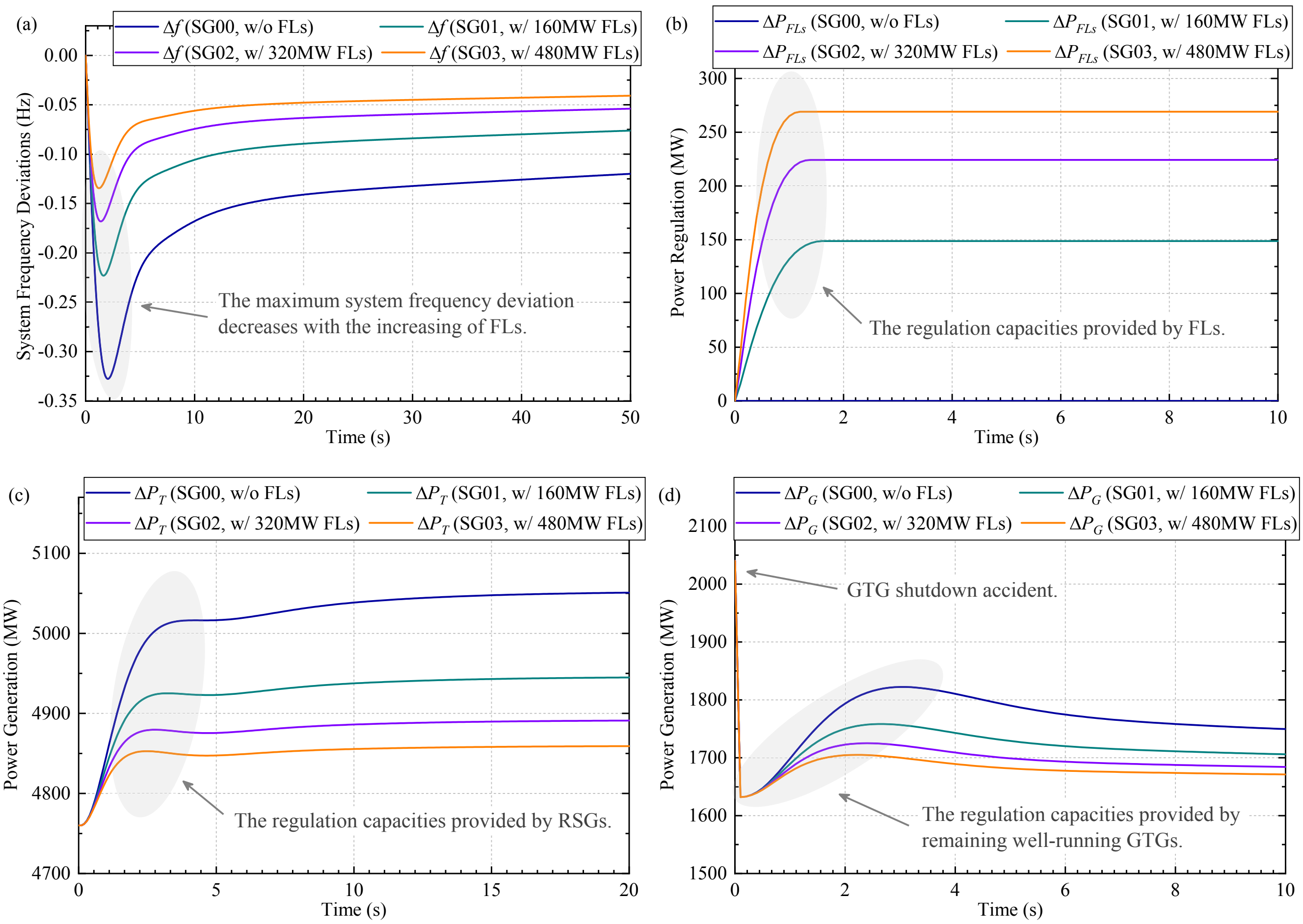


Fig. 11. The frequency deviations of the power system and the regulation power from FLs, RSGs and GTGs, in cases SG00, SG01, SG02, and SG03. (a) Frequency deviation comparisons of the power system; (b) Regulation power comparisons provided by FLs; (c) Regulation power comparisons provided by RSGs; (d) Shutdown accident and regulation power of GTGs.

deviation value can be calculated as

$$\Delta f(t_{k,l}^r) \approx \Delta\widehat{f}\left(t_{k,l}^r\right) = \Delta f_{FLs,l}\left(t_{k,l}^r\right) + \Delta\widehat{f_{FLs,l}}\left(t_{k,l}^r\right) = \Delta f_{FLs,l}\left(t_{k,l}^r\right) + \frac{\Delta f_{FLs,l}\left(t_{k,l}^r\right) - \Delta f_{FLs,l}\left(t_{k-1,l}^r\right)}{t_k^s - t_{k-1}^s}(t_{k,l}^r - t_k^s) \tag{24}$$

The estimation precision of frequency deviations, and the proposed reconstructed power system model considering FLs will be illustrated using numerical studies in Section 5.

5. Numerical studies

5.1. Test system

In this section, the power system with multiple generating units in Fig. 1(a) is adopted as the test system. Based on the actual power systems' data [2,45], the rated capacity of the power system is set as 8000 MW. The rated frequency is 60 Hz. The total number of generating units is 12, including 7 RSGs and 5 GTGs, respectively. The rated operating power capacities of RSGs and GTGs are 800 MW and 480 MW, respectively. The remaining parameters of the RSGs and GTGs are set as shown in Table 1.

It is assumed that the power system is without FLs in Case 1 ($\alpha_{DR} = 0\%$), with 160 MW FLs in Case 2 ($\alpha_{DR} = 2\%$), with 320 MW FLs in Case 3 ($\alpha_{DR} = 4\%$), and with 480 MW FLs in Case 4 ($\alpha_{DR} = 6\%$), respectively. Besides, the communication time-delay during control process of FLs is considered to be 0 ms, 50 ms, 200 ms, and 500 ms in different scenarios, respectively. The initial operating power of the system is 6800 MW. One GTG shutdown accident, and one RSG shutdown accident are assumed to be the accidental outages, respectively. Therefore, all the case studies can be summed up in Table 2, where the shadow areas can be utilized to test the proposed ATDC scheme.

In Table 2, the cases of SG00, SG01, SG02, and SG03 can be utilized to illustrate the effectiveness of FLs for improving the power systems' dynamic performances in accidental outages. Cases of SG11, SG21, and SG31 can be analyzed to study the impacts of time-delay on FLs' control. Cases of SG11, SG12, and SG13 can be used to compare differences of various FLs' capacities under the same time-delay. Cases from SG11 to SG33 can verify the effectiveness of the proposed ATDC scheme. The two scenarios, GTG shutdown and RSG shutdown accidents, can verify the impacts of different types of generating units' shutdown accidents on power systems' stability.

The test system is formulated by utilizing the Simulink Model of Matlab R2015b, on a computer with Intel(R) Core(TM) i7-5500U processors, clocking at 2.40 GHz. The step size is set to be 0.1 s, i.e., the system frequency deviations are assumed to be detected and transmitted to FLs per 0.1 s. The implementation procedure of the test system is shown in Fig. 9.

There are four main steps of the implementation procedure: (i) Initialization of parameters to simulate power systems with flexible loads; (ii) Aggregator monitors the system frequency deviations in real time; (iii) Aggregator transmits the detected parameters to terminal

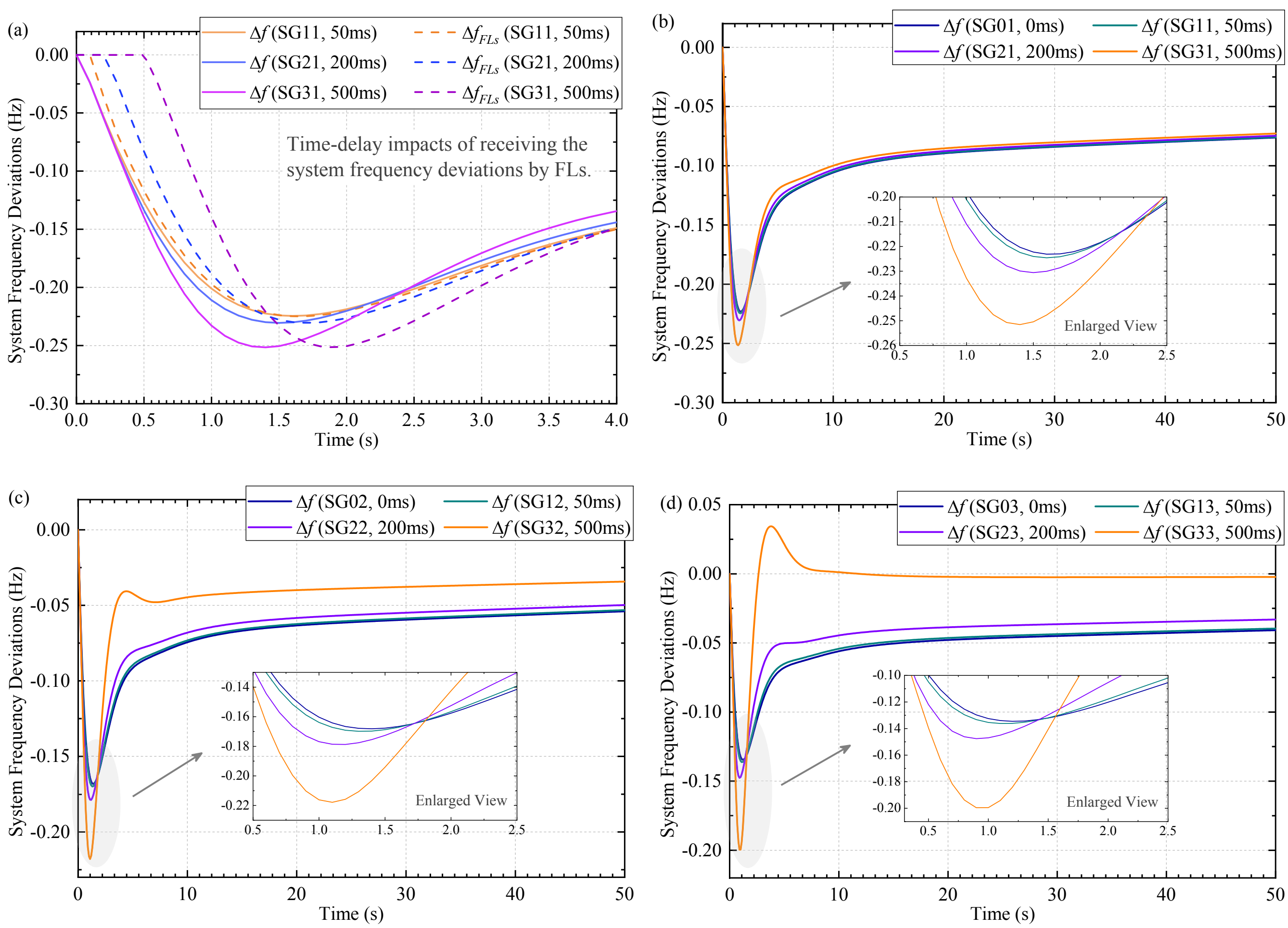


Fig. 12. The power system frequency deviations caused by different communication time-delay, including 0 ms, 50 ms, 200 ms, and 500 ms. (a) Communication time-delay impacts on frequency detections in SG11, SG21, and SG31; (b) Comparisons of frequency deviations in SG01, SG11, SG21, and SG31; (c) Comparisons of frequency deviations in SG02, SG12, SG22, and SG32; (d) Comparisons of frequency deviations in SG03, SG13, SG23, and SG33.

Table 3
The maximum frequency deviations (Hz).

Time-delay	FL capacity			
	0 MW (0%)	160 MW (2%)	320 MW (4%)	480 MW (6%)
0 ms	SG00 −0.3276	SG01 −0.2231	SG02 −0.1682	SG03 −0.1345
50 ms	N/A	SG11 −0.2245	SG12 −0.1698	SG13 −0.1362
200 ms	N/A	SG21 −0.2306	SG22 −0.1787	SG23 −0.1476
500 ms	N/A	SG31 −0.2515	SG32 −0.2178	SG33 −0.1995

controllers; (iv) Each terminal controller takes action to control corresponding FLs. The specific results and discussions are shown as follows.

5.2. Regulation results of generators and flexible loads

When one GTG shutdown accident occurs, the power systems' dynamic performances can be analyzed using Bode diagram, as shown in Fig. 10. The gain margin (Gm) and phase margin (Pm) are two parameters to show the stability margin of the system. The power system will be more stable to resist accidental disturbances with the increasing of Gm and Pm.

It can be seen from Fig. 10(a) that the Gm and Pm are 19.2 dB and 58.8 deg, respectively, in the power system without FLs. In Fig. 10(b), (c), (d), the Gm increases to 20.1 dB, 21.2 dB and 24.2 dB, and the Pm increases to 59.3 deg, 59.7 deg and 60.6 deg, when 160 MW, 320 MW and 480 MW FLs participate in DR, respectively. Therefore, the Gm and Pm of the power system get increased with more FLs participating in DR. It proves that the power system's dynamic performances and stability can be enhanced by FLs.

Fig. 11 shows (a) the dynamic processes of the system frequency deviations, (b) regulation power of FLs, (c) power generation of RSGs, and (d) power generation of GTGs, when one GTG shutdown accident occurs. It can be seen from Fig. 11(a) that the power system's frequency drops rapidly, and recovers to the rated value under the control of FLs, RSGs, and GTGs. The maximum deviation value is −0.3276 Hz in SG00 when there is no FLs. In contrast, the maximum frequency deviation is −0.2231 Hz, −0.1682 Hz, and −0.1345 Hz in SG01, SG02, and SG03, respectively. It verifies the regulation effectiveness of FLs for power systems. The specific regulation power of FLs can be seen in Fig. 11(b).

The regulation power of RSGs and GTGs can be found in Fig. 11(c) and (d), respectively. With the increasing of FLs, the needed regulation power from RSGs and GTGs become less. It illustrates that FLs can relieve the regulating pressure of generating units. Besides, it can be seen from Fig. 11(d) that the generation power of GTGs decreases suddenly, due to the shutdown of one GTG. After that, the remaining well-running GTGs increase power to make up for the lost power, with the cooperation of RSGs and FLs.

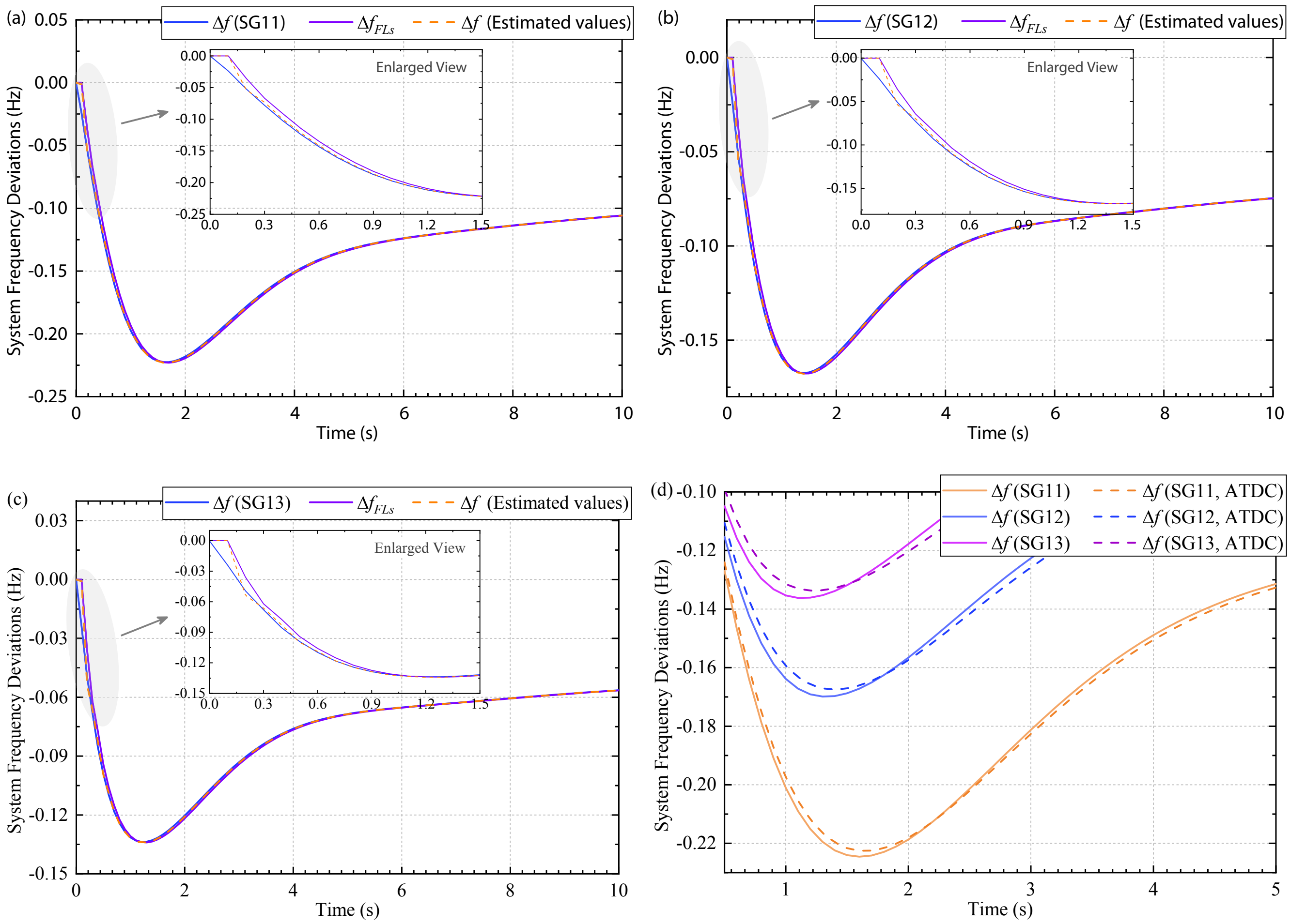


Fig. 13. The correction results of frequency deviations by utilizing the proposed adaptive time-delay control scheme. (a) The actual, FL-receiving and corrected frequency deviations in SG11; (b) The actual, FL-receiving and corrected frequency deviations in SG12; (c) The actual, FL-receiving and corrected frequency deviations in SG13; (d) The frequency deviation comparisons before and after correction by utilizing the proposed adaptive time-delay control scheme in SG11, SG12 and SG13.

5.3. Regulation results of generators and flexile loads considering time-delay

The analyses in Section 5.2 are assumed that the system frequency deviations can be detected and transmitted to the controllers of FLs without time-delay. However, in reality, the communication time-delay is unavoidable. To address this issue, this subsection will study the time-delay impacts on the effectiveness of FLs' control and power system's stability.

Fig. 12(a) shows the actual system frequency deviation values and the receiving values by FLs. The delay time is assumed to be 50 ms, 200 ms, and 500 ms in SG11, SG21, and SG31, respectively. The regulation effectiveness of the system frequency is shown in Fig. 12(b). As for the same FLs' capacities, the maximum frequency deviation value changes from −0.2231 Hz in SG01 to −0.2245 Hz, −0.2306 Hz, and −0.2515 Hz, in SG11, SG21, and SG31, respectively. It illustrates that the FLs' regulation effectiveness get decreased by the increasing time-delay.

Compared with the cases in Fig. 12(b), the results in Fig. 12(c) and (d) are based on larger FLs' capacities. The corresponding maximum frequency deviations are shown in Table 3. In the scenarios of 320 MW FLs, the maximum frequency deviation changes from −0.1682 Hz in SG02 to −0.2178 Hz in SG32. In the scenarios of 480 MW FLs, the maximum frequency deviation expands from −0.1345 Hz in SG03 to −0.1995 Hz in SG33. Therefore, with the increase of FLs' capacities, the regulation effectiveness will be more affected by time-delay. In other words, when the power system includes large-scale FLs, the time-delay should be paid more attention to avoid the negative impacts.

To address the time-delay issues, the ATDC method is used in the control process of FLs. The actual, FL-receiving and corrected frequency deviations are shown in Fig. 13(a), (b), and (c). It can be seen that FLs receive system frequency deviation values later than the actual frequency deviations. By using the ATDC scheme in FLs' controllers, the estimated frequency deviation curves overlap the actual frequency deviation curves almost completely. Therefore, the ATDC scheme can correct the frequency detection errors caused by time-delay.

Moreover, it can be seen from Fig. 13(d) that the maximum frequency deviations decrease to −0.2225 Hz, −0.1675 Hz, and −0.1337 Hz in SG11, SG12, and SG13, respectively, which are less than the original values in Table 3. These results verify the effectiveness of the ATDC scheme for improving the regulation effects of FLs, and decreasing the system frequency deviations.

5.4. Comparisons between different shutdown accidents

The above analyses in Sections 5.2 and 5.3 are based on the GTG shutdown accident. To compare different types of generating unit accidents, this subsection assumes that one RSG shuts down suddenly. The dynamic processes of the system frequency deviations, regulation power of FLs, power generation of RSGs and GTGs are shown in Fig. 14.

Compared with the GTG shutdown accident in Fig. 11, the regulation processes of the RSG shutdown accident are similar. However, as

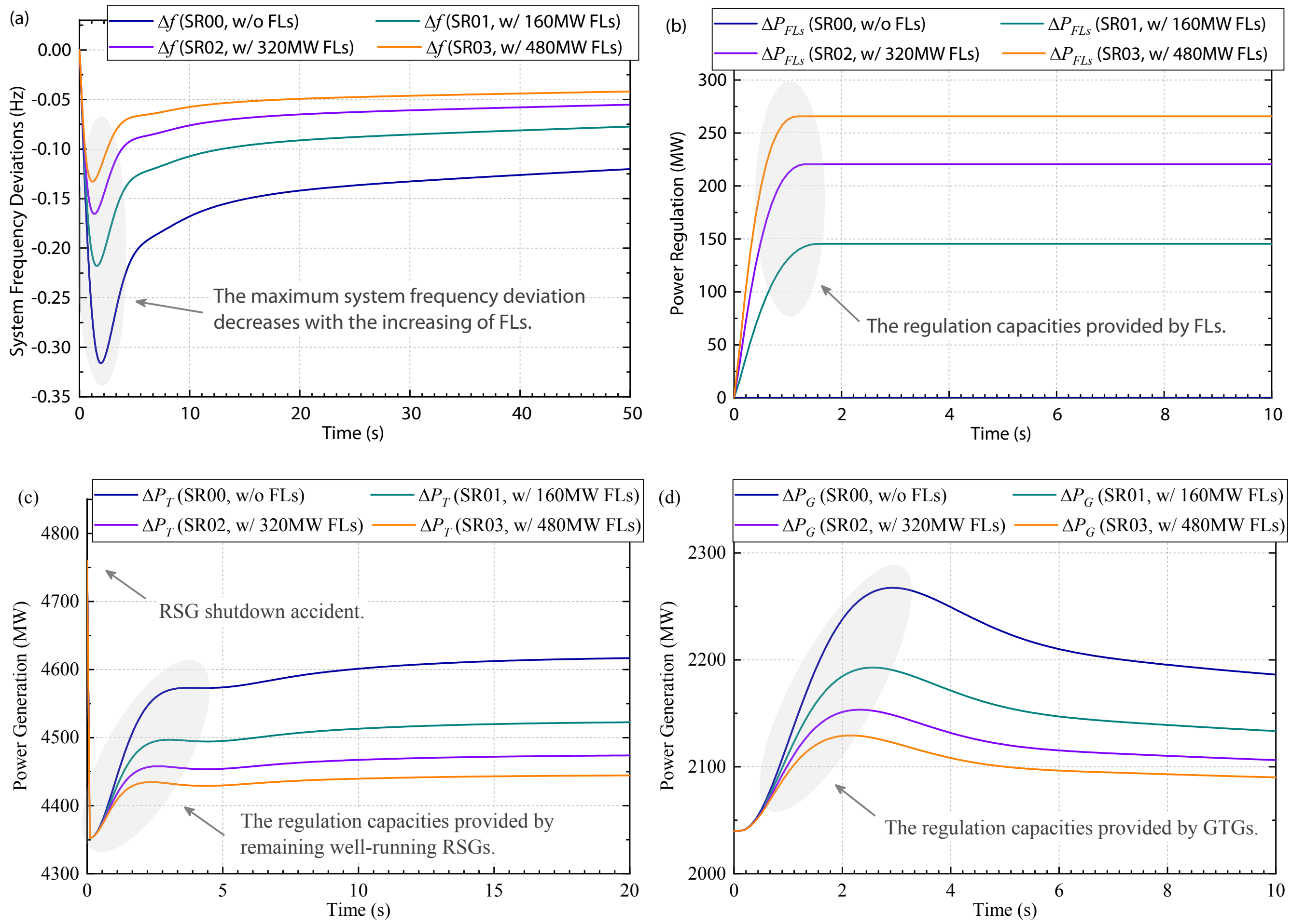


Fig. 14. The frequency deviations of the power system and the regulation power from FLs, RSGs and GTGs in SR00, SR01, SR02, and SR03. (a) Frequency deviation comparisons of the power system; (b) Regulation power comparisons provided by FLs; (c) Shutdown accident and regulation power of RSGs; (d) Regulation power comparisons provided by GTGs.

shown in Fig. 14(c), the generation power of RSGs decreases suddenly, while the generation power of GTGs drops quickly in Fig. 11(d). Besides, the maximum frequency deviation in SR00 is −0.3160 Hz, while it is −0.3276 Hz in SG00. The main reason is that the GTG can be regulated more quickly than RSG. In SR00, all the GTGs operate well, which can increase power generation in a short time to maintain the system balance.

The maximum frequency deviation in SR03 is −0.1329 Hz, which is similar with −0.1345 Hz in SG03. This comparison illustrates that FLs can change the system frequency deviation from a larger value (SG00: −0.3276 Hz) in GTG shutdown accidents than the deviation value (SR00: −0.3160 Hz) in RSG shutdown accidents. In other words, the FLs can make bigger differences in GTG shutdown accidents. Therefore, the regulation power from FLs is more important in actual power systems when the GTG shuts down and affects the system's fast regulation capacities.

Furthermore, the time-delay impacts on the effectiveness of FLs' control are also studied in RSG shutdown accidents, as shown in Fig. 15. The actual system frequency deviation values and the receiving values by FLs are illustrated in Fig. 15(a), where the delay time is assumed to be 50 ms, 200 ms, and 500 ms in SR11, SR21, and SR31, respectively. The regulation effectiveness of the system frequency is shown in Fig. 15(b). As for the same FLs' capacities, the maximum frequency deviation value changes from −0.2180 Hz in SR01 to −0.2194 Hz, −0.2255 Hz, and −0.2465 Hz, in SR11, SR21, and SR31, respectively. Therefore, the FLs' regulation effectiveness get decreased by the time-delay.

Fig. 15(c) and (d) show the actual, FL-receiving and corrected frequency deviations by the ATDC scheme in SR11 and SR12, respectively. It can be seen that the estimated frequency deviation curves overlap the actual frequency deviation curves almost completely. In Fig. 15(c), the maximum frequency deviation decreases from −0.2194 Hz to −0.2174 Hz by ATDC scheme. In Fig. 15(d), the maximum frequency deviation is corrected to −0.1646 Hz in SR12 using ATDC, which is even smaller than the original deviation value −0.1655 Hz in SR02 without time-delay. Therefore, the ATDC scheme can correct the frequency detection errors caused by time-delay, and improve the control effects of FLs.

6. Conclusions

Facing the increasing accidental outages in power systems, this paper proposes using demand response (DR) to provide contingency reserve capacities by adjusting the power consumption of flexible loads (FLs). The novel power system model after accidental outages is reconstructed to obtain the regulation power from well-running generating units. On this basis, FLs are modelled and integrated into power systems to be as an alternative method of making up for the fast regulation capacities. The stochastic decision method and adaptive time-delay control (ATDC) scheme are utilized to control aggregated FLs for achieving smooth regulation of capacities, and decreasing the impacts of communication time-delay on system stability. The results show that the power system's dynamic performances and stability can be enhanced by FLs. However, the FLs' regulation effectiveness can be

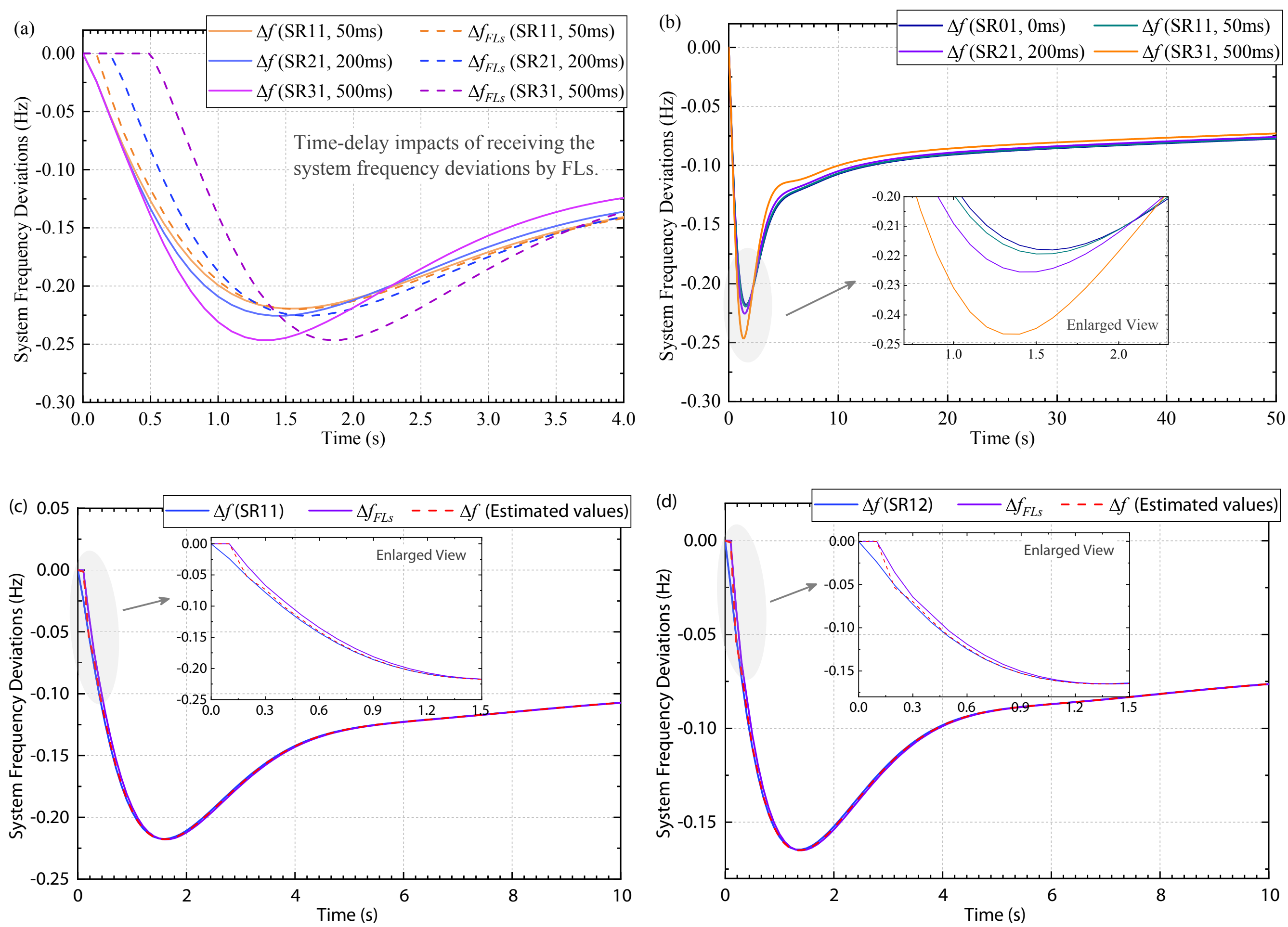


Fig. 15. The communication time-delay impacts and correction results of frequency deviations by utilizing the proposed adaptive time-delay control scheme. (a) Communication time-delay impacts on frequency detections in SR11, SR21, and SR31; (b) Comparisons of frequency deviations in SR01, SR11, SR21, and SR31; (c) The actual, FL-receiving and corrected frequency deviations in SR11; (d) The actual, FL-receiving and corrected frequency deviations in SR12.

affected and decreased by the time-delay, especially for the power system with larger number of FLs. By using the ATDC method in FLs' controllers, the estimated frequency deviation values are corrected to almost overlap the actual frequency deviations, so as to decrease the errors of FLs' regulation capacities caused by time-delay. In the gas turbine generator (GTG) shutdown accident, the maximum frequency deviation is decreased from -0.3276 Hz to -0.1337 Hz by the ATDC scheme of FLs. Moreover, by comparing GTG shutdown accidents and reheat steam generator (RSG) shutdown accidents, the regulation power from FLs shows more importance in GTG shutdown accidents, due to the reduction of fast regulation capacities with the shutdown of GTGs. Therefore, in the actual power systems with high proportion of GTGs, the FLs should be paid more attention to be as an alternative of making up for the fast regulation capacities.

This paper carries out a study on the control method of FLs in power systems facing accidental outages. It considers the impact of communication system and proposes an ATDC scheme to solve the time-delay problem. This paper can provide important and practical references for developing DR in the future smart grid paradigm.

7. Future work

Apart from the most serious accidental outage studied in this paper, other kinds of generating units' outages will be further investigated in our future research. Besides, the control methods of FLs in multi-area power systems will be studied by considering the tie-line power deviations. The control methods of FLs in smart grid paradigm by utilizing new communication technologies (e.g., 5G net-work) will also be studied in our future work.

CRediT authorship contribution statement

Hongxun Hui: Conceptualization, Methodology, Software, Validation, Visualization, Writing - original draft. **Yi Ding:** Investigation, Resources, Writing - review & editing, Supervision. **Yonghua Song:** Data curation, Supervision, Project administration.

Declaration of Competing Interest

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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Appendix A

The test system is formulated by utilizing the Simulink Model of Matlab R2015b, on a computer with Intel(R) Core(TM) i7-5500U processors, clocking at 2.40 GHz. Part of the Simulink model is shown in Fig. 16.

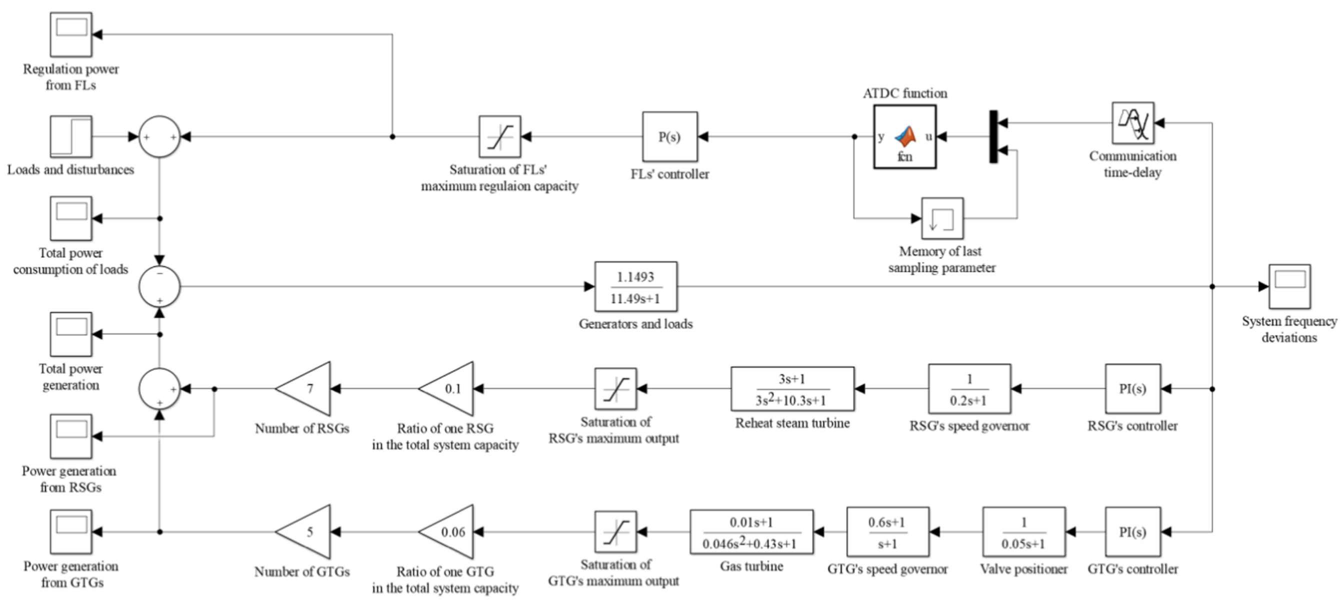

Fig. 16. Simulink model of the adaptive time-delay control of flexible loads in the test system.

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