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Anticipatory Control of Flexible Loads for System Resilience Enhancement Facing Accidental Outages

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***Abstract*—The accidental outages of generating units are increasing rapidly around the world due to extreme weather, cyber attacks and some manual misoperations, which are seriously impacting the stable and secure operation of urban power systems. To enhance the system resilience, more attentions are paid to regulating flexible loads (FLs) in demand-side by utilizing the progressed Internet of Things technologies. However, most previous control methods of FLs are based on the detected frequency deviations or voltage violations, i.e., the regulation on FLs are implemented after the imbalance really happens. This may lead to the expansion of the accident influence and cause large-scale blackouts. To address this issue, this paper proposes an anticipatory control method of FLs to provide faster-than-real-time contingency reserve for the power system. Firstly, a reconstructed power system model after accidental outages is proposed to quantify the disturbance of generating units' outages. Then, an evaluation method of the system frequency deviation nadir is developed to prejudge the most serious damage caused by accidental outages. On this basis, an anticipatory control method of FLs is proposed to impede the fast drop of the system frequency and decrease the harm of accidental outages. Finally, the effectiveness of the proposed method is verified by numerical studies, where the evaluation accuracy of the system frequency nadir can reach about 95% and the maximum system frequency deviation can be reduced about 50%.**

***Index Terms*—Anticipatory control, flexible load, power system resilience, accidental outage.**

I. INTRODUCTION

The accidental outages of generating units are increasing rapidly in power systems around the world. For example, on Aug. 9, 2019, two large generators got separated from the system due to accidental lightning strikes in UK, which caused about 1,880MW power output loss and impacted 1 million users [1]. On Dec. 23, 2015, Ukrainian Power Grid sustained a sudden blackout due to coordinated cyber attacks [2]. On May 13, 2021, four generating units shut down accidentally due to the manual misoperation in Taiwan China, which caused a large-scale blackout and impacted around 4 million users [3]. In Texas US, the extreme cold weather caused lots of gas generating units and wind turbines to be shut down during several days in Feb. 2021, which resulted in serious blackout and impacted more than 4.8 million users [4]. These incidents show that the accidental outages of generating units have serious consequences for the power system. An important fundamental measure to decrease the accidental outage impact is to improve the system contingency reserve capacity to enhance the system resilience in extreme scenarios, which is especially crucial for the near future power system with high-penetration renewable generating resources [5].

With the development of Internet of Things technologies [6], flexible loads (FLs) in demand-side are given high expectations to be reserve resources and provide regulation services for the power system. For example, Huang et al. [7] propose an optimization method to regulate distributed photovoltaic power and batteries in the multi-energy industrial micro-grid, which proves that the demand-side resources' flexibility can release the stress of the main grid. Tao et al. [8] develop the commercial building models as virtual power plants to provide ancillary services for the power system. Siano et al. [9] design a real-time distribution energy market to make full use of residential appliances' flexibility for utilizing renewable energies, which proves that both the distribution network and users can get benefits. Shao et al. [10] utilize the FLs' heat demand and electricity demand to provide balancing resources for the power system, which achieves fluctuating wind power to be better integrated into the power system. Song et al. [11] model air conditioners as batteries to provide flexible regulation services for the power system. Chen et al. [12] propose a learning-based optimal power flow model considering the flexibility of thermostatically controlled loads, in which the power imbalances, voltage violations and current violations are verified to be alleviated by regulating FLs. Zhou et al. [13] propose a novel multi-level cyber-attack resilient distributed control scheme for demand-side resources to timely isolate corrupted links and controllers, which can be against the time-varying and successive attacks effectively in micro-grid. Shi et al. [14] propose an optimal allocation strategy for fuel-based distributed generators to enhance the system resilience against extreme weather.

These studies can be categorized into two kinds: the first kind is based on optimization methods; the second kind is based on control methods. Generally, the optimization of FLs is implemented before the dispatch interval or day-ahead [15]. At that time, the stochastic accidental outages cannot be fully considered. Even though some studies propose distributionally robust chance-constrained optimization methods [16], the fundamentally effective way is to increase the contingency reserve capacity. It may increase the system operation cost.

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By contrast, the control of FLs is generally implemented after the accidental outages really happen, in which the regulation strategies of FLs are decided by detecting the system frequency deviations or voltage violations [17]. With the increase of frequency deviations and voltage violations, more FLs are regulated to provide reserve capacities for the power system. That is to say, the regulation capacity of FLs is decided after the corresponding imbalance, which is "hindsight" and may lead to the expansion of the accident influence (e.g., the emergency load shedding and the relay protection action).

In this paper, we want to design an anticipatory control method of FLs, which can evaluate the impact degree of accidental outages in a short time (e.g., 1s) and then control FLs to provide contingency reserve before the serious accident really happens. However, there are *two difficulties* for achieving this anticipatory control:

Complex power system model: The power system generally have multi-machines with lots of model parameters, including the governor speed regulation parameters, governor time constants, steam chest time constants, reheat time constants, high-pressure turbine fraction parameters and so on [18]. When some generators occur accidental outages, it is complex to develop the novel power system model with the specific breakdown generators in a short time. Besides, the generators' operation states are related to the real-time power system state, including the loads, power flow and some constraints [19]. The indistinct model and operation states further ratchet up the quantitative evaluation difficulty of the accidental outage's impact to the power system.

Stochastic accidental outages: Most accidental outages of generators are stochastic and unpredictable in the power system [20], which causes traditional control methods of FLs have to start up after the frequency deviations or voltage violations really happen. If we want to regulate FLs to provide faster-than-real-time contingency reserve, the probable impact degree of the accidental outage should be evaluated instantaneously. Considering the real-time dynamic system states, the damage of stochastic accidental outages is difficult to be prejudged.

To address aforementioned issues, this paper makes several research progresses, which can be summarized as follows:

1) An equivalent aggregated single-machine system frequency response (SFR) model is developed from multi-machine SFR model. On this basis, a reconstructed single-machine SFR model after accidental outages is proposed to quantify the disturbance caused by generating units' outages.
2) A simplification method of the power system frequency deviation process is formulated theoretically. Based on this, an evaluation method of the system frequency deviation nadir value and corresponding time are developed to prejudge the most serious damage due to the accidental outages.
3) An anticipatory control method of FLs is proposed to impede the fast drop of the system frequency and decrease the harm of accidental outages. The numerical studies illustrate that the evaluation accuracy of the system frequency nadir can reach about 95% and the maximum system frequency deviation can be reduced about 50%.

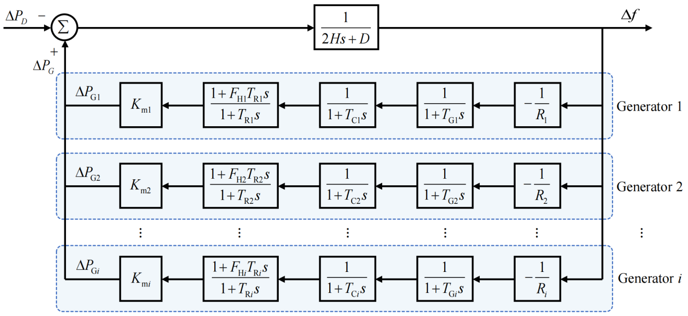

Fig. 1. The typical multi-machine system frequency response model.

The remainder of this paper is organized as follows. Section II formulates the SFR model, including the multi-machine SFR model and aggregated single-machine SFR model. The frequency nadir evaluation method and the anticipatory control method of FLs are presented in Section III. Numerical studies are illustrated in Section IV. Section V concludes this paper.

II. SYSTEM FREQUENCY RESPONSE MODEL

A. Multi-machine SFR Model

A typical multi-machine SFR model is shown in Fig. 1, in which the machines are assumed to be reheat steam generators (the most common generators) [21]. The power system frequency deviations can be calculated by:

$$\Delta f(s) = \frac{1}{2Hs+D}\left(\Delta P_{\mathrm{G}}(s) - \Delta P_{\mathrm{D}}(s)\right), \tag{1}$$

where H and D are the system inertia constant and damping factor, respectively. Symbol s is the Laplace operator.

Symbol ΔP_G is the output power adjustment value of all the generators, which can be obtained by:

$$\Delta P_{\mathrm{G}}(s) = -\sum_{i\in\mathcal{I}} \frac{K_{\mathrm{m}i}(1+F_{\mathrm{H}i}T_{\mathrm{R}i}s)\Delta f(s)}{R_i(1+T_{\mathrm{R}i}s)(1+T_{\mathrm{C}i}s)(1+T_{\mathrm{G}i}s)}, \tag{2}$$

where R_i is the i-th generator's governor speed regulation parameter; $T_{\mathrm{G}i}$ is the i-th generator's governor time constant; $T_{\mathrm{C}i}$ is the i-th generator's steam chest time constant; $T_{\mathrm{R}i}$ is the i-th generator's reheat time constant; $F_{\mathrm{H}i}$ is the i-th generator's high-pressure turbine fraction; $K_{\mathrm{m}i}$ is the i-th generator's mechanical power gain factor.

Symbol ΔP_D is the disturbance to the power system. Generally, a sudden disturbance can be regarded as a step function, and expressed in the Laplace domain as:

$$\Delta P_{\mathrm{D}}(s) = \frac{P_{\mathrm{step}}}{s}, \tag{3}$$

where P_{step} is the disturbance magnitude in per unit w.r.t. the system installed generation capacity S_{sys}. The system capacity can be calculated by summing all the generators' capacities S_i:

$$S_{\mathrm{sys}} = \sum\nolimits_{i\in\mathcal{I}} S_i. \tag{4}$$

The system inertia constant H is defined to reflect the average behavior of all the generators in the system, which is calculated by:

$$H = \sum\nolimits_{i\in\mathcal{I}} H_i S_i \Big/ S_{\text{sys}}, \tag{5}$$

where H_i is the i-th generator's inertia constant.

B. Aggregated Single-machine SFR Model

To simplify the analysis of the overall system frequency deviations, the multi-machine SFR model in Fig. 1 can be equivalent to an aggregated single-machine SFR model [22], as shown in Fig. 2. The output power adjustment value of generators can be expressed as:

$$\Delta P_{\mathrm{G}}(s) = -\frac{(1+F_{\mathrm{H}}T_{\mathrm{R}}s)\Delta f(s)}{R(1+T_{\mathrm{R}}s)(1+T_{\mathrm{C}}s)(1+T_{\mathrm{G}}s)}, \tag{6}$$

where the equivalent governor speed regulation parameter R is obtained by:

$$\frac{1}{R} = \sum\nolimits_{i\in\mathcal{I}} \frac{K_{\mathrm{m}i}}{R_i} = \sum\nolimits_{i\in\mathcal{I}} \kappa_i. \tag{7}$$

The equivalent governor time constant T_{G}, the equivalent steam chest time constant T_{C}, the equivalent reheat time constant T_{R}, and the equivalent high-pressure turbine fraction F_{H} can be calculated by:

$$\frac{1}{1+T_{\mathrm{G}}s} = \sum_{i\in\mathcal{I}} \lambda_i \frac{1}{1+T_{\mathrm{G}i}s}, \tag{8}$$

$$\frac{1}{1+T_{\mathrm{C}}s} = \sum_{i\in\mathcal{I}} \lambda_i \frac{1}{1+T_{\mathrm{C}i}s}, \tag{9}$$

$$\frac{1+F_{\mathrm{H}}T_{\mathrm{R}}s}{1+T_{\mathrm{R}}s} = \sum_{i\in\mathcal{I}} \lambda_i \frac{1+F_{\mathrm{H}i}T_{\mathrm{R}i}s}{1+T_{\mathrm{R}i}s}, \tag{10}$$

where λ_i is a normalization factor and defined as:

$$\lambda_i = \kappa_i \Big/ \sum\nolimits_{i\in\mathcal{I}} \kappa_i, \tag{11}$$

where $\sum_{i\in\mathcal{I}} \lambda_i = 1$.

C. Reconstructed SFR Model After Accidental Outages

When the disturbance P_{step} comes from loads, the number of online generators keeps constant. All the online generators can increase the output power (if they have the regulation capacity) to deal with this disturbance. However, when the disturbance is caused by accidental outages, some generators will disconnect from the system. Compared with the same magnitude disturbance caused by loads, the accidental outages have a more serious impact on the power system operation [23]. The disturbance of accidental outages can expressed as:

$$P_{\text{step}} = \sum_{i\in\mathcal{I}, i\in\Gamma} P_{\mathrm{G}i}^{0}, \tag{12}$$

where $P_{\mathrm{G}i}^{0}$ is the i-th generator's initial output power before the accidental outage. Symbol Γ indicates the set of shutdown generators, which is a subset of $\mathcal{I}$, i.e., $\Gamma \subset \mathcal{I}$.

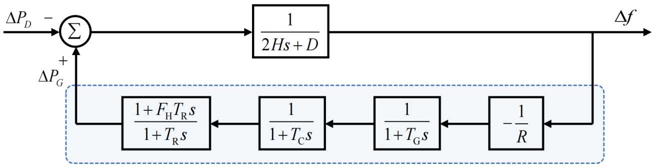

Fig. 2. The aggregated single-machine system frequency response model.

Then, the output power adjustment value of generators in Eq. (6) after the accidental outage can be reconstructed as:

$$\begin{aligned}\Delta \widehat{P}_{\mathrm{G}}(s) &= -\sum_{i\in\mathcal{I}, i\notin\Gamma} \frac{K_{\mathrm{m}i}(1+F_{\mathrm{H}i}T_{\mathrm{R}i}s)\Delta f(s)}{R_i(1+T_{\mathrm{R}i}s)(1+T_{\mathrm{C}i}s)(1+T_{\mathrm{G}i}s)} \\ &= -\frac{(1+\widehat{F}_{\mathrm{H}}\widehat{T}_{\mathrm{R}}s)\Delta f(s)}{\widehat{R}(1+\widehat{T}_{\mathrm{R}}s)(1+\widehat{T}_{\mathrm{C}}s)(1+\widehat{T}_{\mathrm{G}}s)},\end{aligned} \tag{13}$$

where $\widehat{(\cdot)}$ indicates the recalculated equivalent parameters based on Eqs. (7)-(11).

III. FREQUENCY NADIR EVALUATION AND ANTICIPATORY CONTROL OF FLEXIBLE LOADS

A. Formulation of Frequency Deviation Process

The reheat time constant $\widehat{T}_{\mathrm{R}}$ is the most significant time constant in Eq. (13), which is generally 6∼14s and can dominate the reheat steam generator's response [24]. Compared with $\widehat{T}_{\mathrm{R}}$, the governor time constant $\widehat{T}_{\mathrm{G}}$ (generally 0.15∼0.3s) and the steam chest time constant $\widehat{T}_{\mathrm{C}}$ (generally 0.2∼0.5s) are very small and can be ignored [21]. Therefore, the Eq. (13) can be approximated by:

$$\Delta \widehat{P}_{\mathrm{G}}(s) \approx -\frac{(1+\widehat{F}_{\mathrm{H}}\widehat{T}_{\mathrm{R}}s)\Delta f(s)}{\widehat{R}(1+\widehat{T}_{\mathrm{R}}s)}. \tag{14}$$

Based on Eqs. (1), (3) and (12)-(14), we can obtain the power system frequency deviations as:

$$\Delta f(s) = \frac{\widehat{R}\omega_n^2}{D\widehat{R}+1} \cdot \frac{(1+\widehat{T}_{\mathrm{R}}s)P_{\text{step}}}{s(s^2+2\varsigma\omega_n s+\omega_n^2)}, \tag{15}$$

where ω_n and ς are the oscillation frequency and the damping coefficient, which can be calculated as:

$$\omega_n^2 = \frac{D\widehat{R}+1}{2\widehat{H}\widehat{R}\widehat{T}_{\mathrm{R}}}, \tag{16}$$

$$\varsigma = \frac{2\widehat{H}\widehat{R}+(D\widehat{R}+\widehat{F}_{\mathrm{H}})\widehat{T}_{\mathrm{R}}}{2(D\widehat{R}+1)}\omega_n. \tag{17}$$

By utilizing the inverse Laplace transform, Eq. (15) in complex-frequency-domain can be transformed into the form of time-domain, as follows:

$$\Delta f(t) = \frac{\widehat{R}P_{\text{step}}}{D\widehat{R}+1}\left[1+\alpha e^{-\varsigma\omega_n t} sin(\omega_r t+\phi)\right], \tag{18}$$

where α and ω_r can be obtained by:

$$\alpha = \sqrt{\frac{1-2\widehat{T}_{\mathrm{R}}\varsigma\omega_n+\widehat{T}_{\mathrm{R}}^2\omega_n^2}{1-\varsigma^2}}, \tag{19}$$

$$\omega_r = \omega_n\sqrt{1-\varsigma^2} \qquad (\varsigma < 1). \tag{20}$$

Get derivative with respect to the time t, and let the equation be equal to 0, i.e., $\mathrm{d}\Delta f(t)/\mathrm{d}t = 0$. We can obtain the time of the system frequency reaching the nadir value:

$$t_{\text{nadir}} = \frac{1}{\omega_r}\tan^{-1}\left(\frac{\omega_r \widehat{T}_{\text{R}}}{\varsigma\omega_n \widehat{T}_{\text{R}} - 1}\right). \tag{21}$$

Then, substitute the Eq. (21) into the Eq. (18), we can get the nadir value of the power system frequency deviation Δf_{nadir}.

B. Frequency Nadir Evaluation After Accidental Outages

Fig. 3 shows a typical power system frequency deviation process. For evaluating the frequency nadir after accidental outages, the frequency deviation curve $\Delta f(t)$ during the time period from t_0 to t_{nadir} can be fitted by a quadratic curve $g(t)$ [25]. It is assumed that the power system is in the stable state at time t_0 and the frequency deviation is zero, i.e., $\Delta f(t_0) = 0$. Then, the fitting quadratic curve does not have the constant term and can be expressed as:

$$g(t) = at^2 + bt. \tag{22}$$

From Eq. (21), we know that the time t_{nadir} is irrelevant to the disturbance magnitude P_{step}, which can be calculated by the inherent parameters of the power system. In other words, no matter how much the stochastic disturbance is, the coefficients a and b satisfy the relationship of $t_{\text{nadir}} = -b/2a$. Therefore, the Eq. (22) can be rewrote as:

$$g(t) = at^2 - 2at_{\text{nadir}}t = a(t^2 - 2t_{\text{nadir}}t) = a\widetilde{g}(t). \tag{23}$$

Next, we want to obtain the parameter a based on the sampling points. As shown in Fig. 3, the sampling points are $[t_0, t_1, \ldots, t_j]$ and the corresponding frequency deviations are $[\Delta f(t_0), \Delta f(t_1), \ldots, \Delta f(t_j)]$. Based on the least square method, the optimization problem can be expressed as:

$$\text{Min} \sum\nolimits_{j\in\mathcal{J}} \left[g(t_j) - \Delta f(t_j)\right]^2. \tag{24}$$

The Eq. (24) is a quadratic function w.r.t. the variable a. It gets the minimum value when the variable is equal to:

$$\widetilde{a} = \sum\nolimits_{j\in\mathcal{J}} \widetilde{g}(t_j)\Delta f(t_j) \Big/ \sum\nolimits_{j\in\mathcal{J}} \widetilde{g}^2(t_j). \tag{25}$$

Substitute $\widetilde{a}$ and t_{nadir} into the Eq. (23), we can obtain the evaluated frequency nadir value:

$$\Delta\widetilde{f}_{\text{nadir}} = g(t_{\text{nadir}}) = -\frac{t_{\text{nadir}}^2 \sum_{j\in\mathcal{J}} \widetilde{g}(t_j)\Delta f(t_j)}{\sum_{j\in\mathcal{J}} \widetilde{g}^2(t_j)}. \tag{26}$$

C. Anticipatory Control of Flexible Loads

It is assumed that the sampling duration time of the system frequency deviation is t_{sample}. When the evaluated frequency nadir $\Delta\widetilde{f}_{\text{nadir}}$ exceeds the threshold Δf_{thr}, the FLs will provide regulation service for the power system. The total available regulation power of FLs is assumed to be $P_{\text{FL}}^{\max}$. In previous studies, the most common control method of FLs is proportional control [17], [24]. In other words, more FLs will be regulated with the increase of power system's frequency deviation $\Delta f(t)$, which can be expressed as:

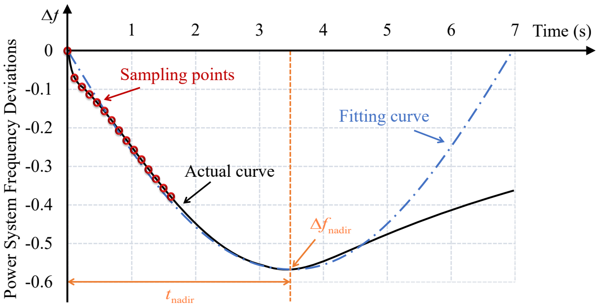

Fig. 3. The actual and fitting curves of the power system frequency deviations.

$$P_{\text{FL}}(t) = \begin{cases} 0, & |\Delta f(t)| \leqslant \Delta f_{\text{thr}}, \\ \eta\Delta f(t), & \Delta f_{\text{thr}} < |\Delta f(t)| < \Delta f_{\max}, \\ P_{\text{FL}}^{\max}, & |\Delta f(t)| \geqslant \Delta f_{\max}, \end{cases} \tag{27}$$

where η is the proportional adjustment factor of FLs. However, this kind of regulation has to be carried out after the frequency deviation $\Delta f(t)$ really happens.

In this paper, we propose the anticipatory control method of FLs to achieve an advanced control, so that the fast system's frequency drop can be impeded earlier. Considering that different levels of accidental outages have different impact degrees on the system stability, larger regulation capacity of FLs should be dispatched faced with more serious accidental outages. Therefore, according to the evaluated frequency nadir $\Delta\widetilde{f}_{\text{nadir}}$, the maximum regulation capacity of FLs (i.e., the adjustment value of FLs at the time t_{nadir}) is calculated by:

$$P_{\text{FL}}^{\text{nadir}} = \begin{cases} 0, & |\Delta\widetilde{f}_{\text{nadir}}| \leqslant \Delta f_{\text{thr}}, \\ \zeta\Delta\widetilde{f}_{\text{nadir}}, & \Delta f_{\text{thr}} < |\Delta\widetilde{f}_{\text{nadir}}| < \Delta f_{\max}, \\ P_{\text{FL}}^{\max}, & |\Delta\widetilde{f}_{\text{nadir}}| \geqslant \Delta f_{\max}, \end{cases} \tag{28}$$

where $P_{\text{FL}}^{\text{nadir}}$ is the adjustment value of FLs at the time t_{nadir}; ζ is the nadir adjustment factor of FLs. It can be seen that partial FLs will be regulated when the evaluated frequency nadir exceeds Δf_{thr}, and all the FLs will be regulated when the evaluated frequency nadir exceeds $\Delta f_{\max}$.

However, the $P_{\text{FL}}^{\text{nadir}}$ cannot be carried out directly before the system frequency drops to the nadir value, because it may lead to the reverse excess regulation. Therefore, according to the frequency dropping process from t_{sample} to t_{nadir}, we design the regulation power of FLs as:

$$P_{\text{FL}}(t) = \frac{t - t_{\text{sample}}}{t_{\text{nadir}} - t_{\text{sample}}}\gamma P_{\text{FL}}^{\text{nadir}}, \tag{29}$$

where γ is the anticipatory regulation factor of FLs. Based on the Eqs. (28)-(29), the regulation power of FLs can be increased gradually during the frequency dropping time.

Note that the t_{nadir} in practical power system is generally around 5∼15s, and the t_{sample} should be less than t_{nadir} (i.e., $t_{\text{sample}} < t_{\text{nadir}}$). Based on the requirement of phasor measurement unit (PMU) [26], the data acquisition frequency should not be less than 100 times per second, i.e., the data acquisition

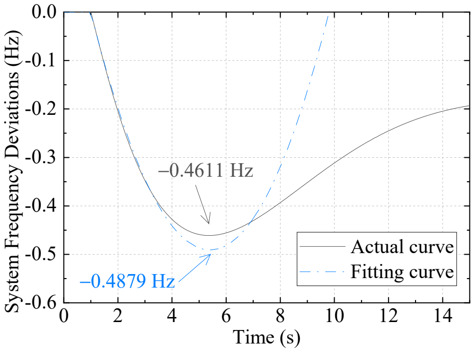

Fig. 4. The actual and fitting curves of the power system frequency deviations in Case 1, i.e., one reheat steam generator is shut down suddenly.

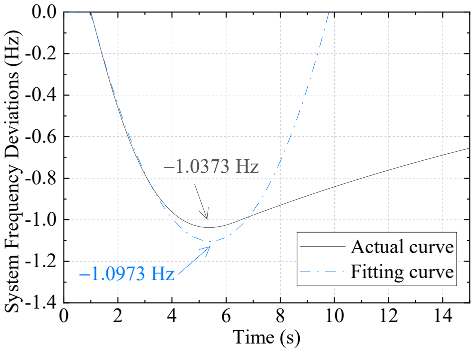

Fig. 5. The actual and fitting curves of the power system frequency deviations in Case 2, i.e., two reheat steam generators are shut down suddenly.

time interval should not be more than 0.01s. Therefore, there are at least 100 sampling points if the t_{sample} is set as 1s, which is enough for obtaining the fitting curve and evaluating the frequency nadir.

IV. CASE STUDY

A. Test System

The test system adopts a typical multi-machine system, as shown in Fig. 1. It is assumed that there are 10 reheat steam generators with the following parameters [23]: $R_i = 0.05$, $T_{\text{G}i} = 0.20s$, $T_{\text{C}i} = 0.30s$, $T_{\text{R}i} = 10.00s$, $F_{\text{H}i} = 0.30$, $K_{\text{m}i} = 0.95$. The system total installed capacity S_{sys} is 8,000MVA. The system rated frequency is 50Hz. The initial operating load is assumed to be 6,400MW. The sampling duration time t_{sample} is set as 1s. The data acquisition time interval is set as 0.01s. Besides, it is assumed that 10% of loads are flexible loads, which can be controlled to provide regulation services for the power system. The adjustment factors of FLs η and ζ are both set as 0.1p.u./Hz. The anticipatory regulation factor of FLs γ is 10. Two accidental outage cases are compared: one reheat steam generator is shut down suddenly in Case 1; two reheat steam generators are shut down suddenly in Case 2.

B. Evaluation Accuracy Analysis of Frequency Deviation

Fig. 4 and Fig. 5 show the power system frequency deviation curves in Case 1 and Case 2, respectively. It can be seen that the frequency deviation curves can be fitted well by the quadratic function based on the sampled frequency points only in the first second. The nadir time t_{nadir} is 4.37s. The evaluated

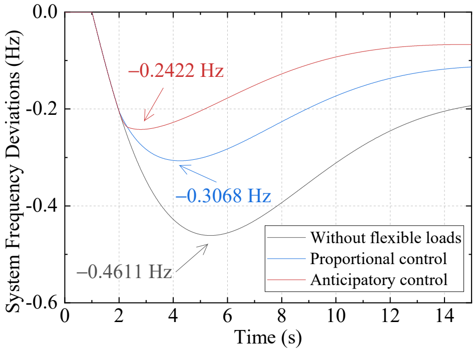

Fig. 6. The frequency regulation results by the traditional proportional control method and the proposed anticipatory control method in Case 1.

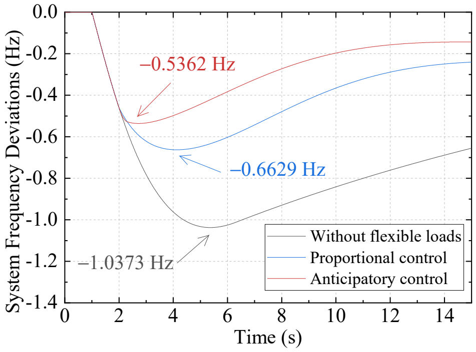

Fig. 7. The frequency regulation results by the traditional proportional control method and the proposed anticipatory control method in Case 2.

coefficients $\widetilde{a}$ are equal to 0.0255 and 0.0575 in Case 1 and Case 2, respectively. On this basis, we can obtain the fitting functions $g(t)$, as follows:

$$g_1(t) = 0.0255t^2 - 0.2233t, \tag{30}$$

$$g_2(t) = 0.0575t^2 - 0.5022t. \tag{31}$$

The frequency nadir can be evaluated by substituting the nadir time t_{nadir} into the Eqs. (30)-(31), as shown in Table. I. In Case 1, the actual frequency nadir is -0.4611Hz and the evaluated value is -0.4879Hz. In Case 2, the actual frequency nadir is -1.0373Hz and the evaluated value is -1.0973Hz. The evaluation errors are only 5.80% and 5.81%, respectively, which are acceptable for regulating FLs in practical system.

TABLE I
EVALUATION RESULTS OF THE SYSTEM FREQUENCY DEVIATION

Cases	t_{nadir}/s	Δf_{nadir}/Hz	$\Delta \widetilde{f}_{\text{nadir}}$/Hz	Error
1	4.37	-0.4611	-0.4879	5.80%
2	4.37	-1.0373	-1.0973	5.81%

C. Frequency Regulation Results by the Anticipatory Control of Flexible Loads

The frequency regulation results by flexible loads in Case 1 and Case 2 are shown in Fig. 6 and Fig. 7, respectively. It can be seen that the frequency nadir in Case 1 can be increased from -0.4611Hz to -0.3068Hz and -0.2422Hz by the traditional proportional control method and the proposed anticipatory control method, respectively. The frequency nadir in Case 2 can be increased from -1.0373Hz to -0.6629Hz and

-0.5362Hz by the traditional proportional control method and the proposed anticipatory control method, respectively. These results verify the effectiveness of regulating FLs for enhancing the power system resilience faced with accidental outages.

TABLE II
FREQUENCY REGULATION RESULTS OF FLEXIBLE LOADS

Cases	Δf_{nadir}/Hz (w/o FLs)	Δf_{nadir}/Hz (proportional)	Raising rate	Δf_{nadir}/Hz (anticipatory)	Raising rate
1	-0.4611	-0.3068	30.68%	-0.2422	47.47%
2	-1.0373	-0.6629	36.09%	-0.5362	48.31%

The adjustment factors of FLs η and ζ are both set as 0.1p.u./Hz, which means the same FLs' capacity will be dispatched under the same frequency deviation scenario. However, the raising rate of the frequency nadir is 30.68% in Case 1 by the proportional control method, and it is 47.47% by the anticipatory control method. It proves that the proposed anticipatory control method has better frequency regulation effect by utilizing the same capacity of FLs, because the proposed anticipatory control method can evaluate the possible frequency nadir and take actions earlier to regulate FLs.

V. CONCLUSION

This paper proposes an anticipatory control method of FLs to provide faster-than-real-time contingency reserve when the power system suffers generating units' accidental outages. Firstly, a reconstructed aggregated single-machine SFR model after accidental outages is developed to quantify the disturbance caused by generating units' outages. Then, an evaluation method of the system frequency deviation nadir value and corresponding time are developed to prejudge the damage of accidental outages. Based on the evaluated consequence, an anticipatory control method of FLs is proposed to impede the fast drop of the system frequency and decrease the harm of accidental outages. Numerical studies illustrate that the evaluation accuracy of the system frequency nadir can reach about 95% only by sampling the frequency points in the first second. Compared with traditional "hindsight" proportional control method of FLs, the proposed anticipatory control method can reduce the maximum system frequency deviation to about 50%, which can provide useful reference for controlling FLs to provide contingency reserve in modern power systems.

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