Demand Response Plan Considering Available Spinning Reserve for System Frequency Restoration

Le-Ren Chang-Chien, *Member, IEEE*, Luu Ngoc An, Ta-Wei Lin

***Abstract*—In the proposed frequency restoration plan, demand response is adopted as the first shedding option for intercepting frequency decline in order to avoid the unexpected load shedding, then followed by the scheduled generation reserve to raise frequency back to the normal state. This paper starts with the frequency response analysis using a low-order frequency response model. Results of the frequency response analysis show that, if the magnitude of system disturbance is accurately estimated following the moment of incident, the estimate could be intelligently used to deploy appropriate demand response for frequency restoration. Tests of the proposed frequency restoration scheme are evaluated by simulation where the system data is utilized by records of historical frequency events from a utility. Test results show that the deployment of the demand response could enhance frequency security under various contingency scenarios.**

***Index Terms*—Demand response, under frequency load shedding, load-frequency control**

I. Introduction

WHEN an electric power system encounters a serious network disturbance or a large unit trip, system frequency would drop substantially and result in malfunction of the network equipment. If the frequency decline is not effectively stopped in a short period of time, cascading events of network failure could further cause a blackout. To avoid the declined frequency that may cause cascading outages, a decisive frequency control using the spinning reserve or load shedding is essential. In most power systems, the Under-Frequency Load Shedding (UFLS) is considered as the last defense line to save system frequency. How the shedding load is applied to save the endangered system frequency has been widely discussed in literatures. The conventional UFLS is designed by monitoring the frequency as an incident index for decision making [1,2]. When the system frequency falls below a predefined threshold, portions of the system load will be shed in a few steps. Although this type of UFLS is simple and easy to be implemented, system operators feel that this scheme has more room to be improved. The major issue of this scheme is its lack of adaptability. Since the amount of the disturbance is unknown. The UFLS scheme is prone to the preset assumption. Its lack of adaptability may result in either over-shedding or under-shedding in different situations. The other approach to avoid this shortcoming is to use the frequency decline rate as an index to measure the disturbance magnitude [2,3]. Using this information, more accurate load could be shed for avoiding the aforementioned drawback. However, the efficacy of this method is dependent upon the accuracy of the rate of frequency change. This method could not perform its prime advantage due to the slow sampling rate of the old SCADA system until the latest introduction of the frequency estimation from the Phasor Measurement Unit (PMU) [4].

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Le-Ren Chang-Chien is, Luu Ngoc An and Ta-Wei Lin were with National Cheng Kung University, No.1 University Rd., Tainan, Taiwan.(E-mail: leren@ee.ncku.edu.tw)

With the fast sampling nature of PMU, accurate disturbance estimation becomes feasible. UFLS could be situated in a better position by knowing how much load is required to be shed for balancing the generation loss. However, shedding the customer load is still risky because the practical shedding amount is not exactly the same as what operators expect. Therefore, in the real practice, operators prefer to shed more load than the estimated value. It may make the following frequency restoration process more complex [5].

Demand Response (DR) refers to actions initiated from contracted customers by changing their consumption (demand) of electric power in response to price signals, incentives, or directions from grid operators. Emergency Demand Response (EDR) program is one of the incentive-based demand response alternatives to provide direct load control, capacity, and ancillary service during the real-time [6]. If EDR is utilized in the UFLS, blocks of EDR selection would make the tripping of load more accurate. System operators would be more confident of the frequency response following the UFLS. Incorporating DR to deal with frequency events is not new, however, how to execute appropriate DR to achieve the responsive and smooth frequency restoration is the issue in need of more investigation.

II. Estimation on the Magnitude of System Disturbance

A. System Frequency Response Model

System frequency is the only observable index that indicates the extent of power imbalance within the system. It goes without saying that the nature of system frequency is a clue to estimate the magnitude of system disturbance. To study the nature of system frequency after the disturbance, we shall begin with the review of system frequency response model [7].

The System Frequency Response (SFR) model is a simplified frequency model used in a real-time for predicting the frequency behavior of a large scale power system subjecting to a disturbance. The basic concept of the model derived here is based on the idea of uniform or averaged frequency, where synchronizing oscillations between generators are filtered out,

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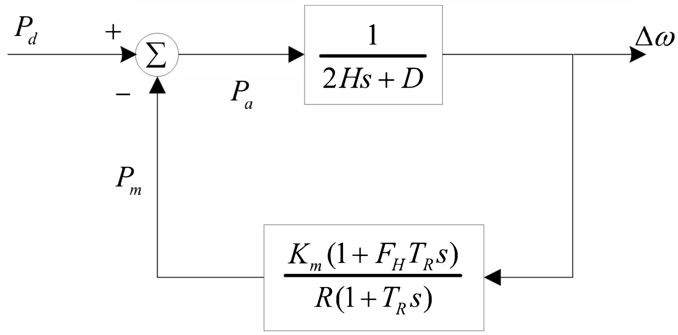

Fig. 1. Simplified SFR model with disturbance input [7].

but the average frequency behavior is retained [7]. The averaging frequency presents the system-wide frequency that would be used for disturbance estimation.

The basic SFR model averages the machine dynamic behavior in a large system into an equivalent single machine. Topologically, we can think of the separate machines being replaced by a single large machine that is connected to the utility network. The SFR model is depicted in Fig. 1.

The nature of SFR model depends on several factors: the gain K_m, the load damping D, the speed-droop of unit governor R, the inertia constant of the system H, the average reheat time constant T_R, and the high pressure power fraction of the reheat turbine F_H. Here we define the "disturbance power" P_d as the system input variable. The sign of P_d is defined as follows:

-$P_d > 0$ For a sudden increase in generation or loss of load

-$P_d < 0$ For a sudden increase in load or loss of generation

For this system model, we compute the frequency response in per unit subject to a unit step disturbance, as shown in the following equation,

$$\Delta\omega = (\frac{R\omega_n^2}{D \times R + K_m})(\frac{1 + T_R s}{s^2 + 2\zeta\omega_n s + \omega_n^2})\frac{P_{step}}{s} \quad (1)$$

where

$\omega_n^2 = \frac{D \times R + K_m}{2H \times R \times T_R}$

$\zeta = (\frac{2H \times R + (D \times R + K_m \times F_H) \times T_R}{2(D \times R + K_m)})\omega_n$

$P_d = P_{step}/s$ is denoted as the unit step disturbance and s is the Laplace operator. Making the slope of $\Delta\omega$ and taking the inverse form for the time domain equation, we get

$$\frac{\Delta\omega(t)}{dt} = \frac{a\omega_n R \times P_{step}}{D \times R + K_m}(e^{-\zeta\omega_n t}\sin(\omega_r t + \varphi)) \quad (2)$$

where

$\omega_r = \omega_n\sqrt{1 - \zeta^2}$

$a = \sqrt{\frac{1 - 2T_R\zeta\omega_n + T_R^2\omega_n^2}{1 - \zeta^2}}$

$\varphi = \tan^{-1}(\frac{\omega_r T_R}{1 - \zeta\omega_n T_R}) - \tan^{-1}(\frac{\sqrt{1 - \zeta^2}}{-\zeta})$

TABLE I
FREQUENCY RESPONSE CALCULATION WITH DIFFERENT SAMPLING RATES

Sampling time (second)	Est. slope (Hz/s)	Exact slope (Hz/s)	Error (%)
1/1000	-3.4247	-3.4278	0.09
1/100	-3.3902	-3.4278	1.10
1/60	-3.3649	-3.4278	1.84
1/40	-3.3333	-3.4278	2.76
1/20	-3.2405	-3.4278	5.47
1/10	-3.0617	-3.4278	10.68
1/8	-2.9758	-3.4278	13.19
1/6	-2.8373	-3.4278	17.23
1/5	-2.7308	-3.4278	20.34

B. Magnitude of System Disturbance

We are particularly interested in the value of (2) at $t = 0$, which corresponds to the maximum rate of change of slope

$$\frac{d\Delta\omega(t)}{dt}|_{t=0} = \frac{a\omega_n R \times P_{step}}{D \times R + K_m}\sin\varphi_1 = \frac{P_{step}}{2H} \quad (3)$$

The initial slope of frequency decline, m_0, is defined as

$$m_0 = \frac{d\Delta\omega(t)}{dt}|_{t=0} = \frac{P_{step}}{2H} \quad (Hz/s) \quad (4)$$

If the initial slope of frequency decline is observed during the incident, we can determine the size of the disturbance as the inertia constant is known. The inertia constant is normalized to the base of the total generation in the network. Generally, its normalized value is about 3 to 5 seconds. This value could also be estimated using the recursive least square algorithm [8]. Consequently, (4) allows us to quickly estimate the size of the disturbance, which is

$$P_{step} = 2H \times m_0 \quad (5)$$

C. Test of the Disturbance Estimation

A disturbance case was tested to verify the accuracy of the disturbance estimation. During the testing case, the estimator kept on monitoring frequency change. Meanwhile, a 0.4 pu generation trip occurred and induced frequency drop. We compared the exact slope of frequency change with the estimated ones with respect to different sampling rates, which are shown in Table I. In Table I, the first two columns record the sampling time and the estimated rate of frequency change with respect to the sampling in Column 1. Column 3 gives the exact rate of frequency change. Column 4 gives the estimation error. Clearly, slower sampling rates make higher errors in the estimation. It is suggested that fast sampling rate can enhance accuracy in frequency slope measurement. Currently, most PMUs are able to sample 60 times within one second. More advanced PMUs can even sample 120 times within one second [9], which is fast enough to reduce the estimation error.

Table I shows that the scale of the sampling time is proportional to the scale of the estimation error. To further enhance the estimation accuracy, [2] proposed the following correction factor.

$$P_{step} = H(\frac{m_0}{30} + \frac{2}{r_s}) \quad (6)$$

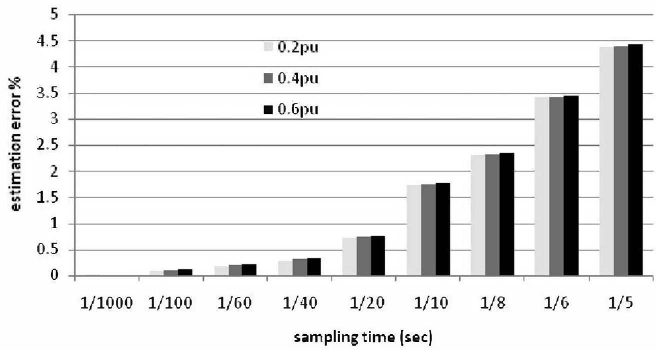

Fig. 2. P_{step} error vs. different sampling with respect to various disturbance magnitudes

where

P_{step}	estimated system disturbance	(pu)
H	system inertial constant	(s)
m_0	estimated slope	(Hz/s)
r_s	sampling rate	(sample/s)

Based on (6), we can deduce that the corrected slope m_0', is as follows.

$$m_0' = m_0 + \frac{60}{r_s} \quad \text{Hz/s} \tag{7}$$

(6) is proven to work well in large systems when frequency decline is not too steep. However, we also found that the correction is not sensitive to the slope of frequency change, m_o, i.e., the disturbance magnitude, which may also affect the accuracy of the estimation error. Therefore, we propose another correction factor to take care of this effect.

$$m_{new}' = m_0 + \frac{m_0}{r_s} \quad \text{Hz/s} \tag{8}$$

Therefore, (6) becomes

$$P_{step} = 2H(\frac{m_{new}'}{60}) \quad \text{Hz/s} \tag{9}$$

After using the correction in (9), Fig. 2 shows the estimation error vs. different sampling with respect to various disturbance magnitudes. The result indicates that the proposed correction factor not only effectively reduces the estimation error (compared to Table I) but also reduces the correction uncertainty that is affected by different disturbance magnitudes.

III. DESIGN OF THE FREQUENCY RESTORATION PLAN CONSIDERING DEMAND RESPONSE AND SPINNING RESERVE

A. Incorporate Direct Load Control Demand Response into the Load Shedding Plan

Direct load control demand response can serve as the reserve capacity for dealing with the frequency events. Shutting down the contracted load (including pumped storage units as they are operating in pumping mode) helps system frequency returning quickly to the acceptable level following the loss of mass generation. However, over-shedding of demand response may make frequency suddenly go beyond the nominal level and result in frequency oscillation, which makes the subsequent frequency restoration process more complicated. Therefore, how to appropriately allocate demand response to rescue the endangered frequency and then facilitate frequency restoration process is the issue in need of more attention.

B. Under Frequency Load Shedding Plan of a Utility

In a utility of our study case, the range of continuous operating frequency is between 59.7, and 60.3Hz. To account for the rate of change of frequency effect, and avoid possible vibration and resonance occurring in some units' turbines, the first stage of load-shedding frequency is set at 59.5Hz with a 50 second time delay. If the first stage load-shedding is not sufficient for stopping the descending frequency, the second stage of under-frequency relay will be initiated immediately to shed customer load when the frequency drop to 59.2Hz [5]. In order not to shed the undesired customer load when frequency reaches 59.2Hz, Emergency Demand Response (EDR) plan is designed according to this defense line. In our design strategy, EDR is divided into two parts. The first part, EDR1, is allocated to prevent the 59.2Hz load shedding. The second part, EDR2, is designed to bring the declined frequency back to a secure level at 59.7Hz so that spinning reserve could carry on the restoration afterwards.

C. Determine the EDR and spinning reserve for Contingency Planning

To deploy sufficient demand response for frequency security, we calculate the least quantity of the demand response (EDR1) for the maximum single contingency (P_{max}) scenario. Assuming that the EDR1 is planned to save the descending frequency from the 59.2Hz frequency level, the required least quantity of EDR1 is equal to the following relation,

$$EDR1 = P_{max} - P_{fmin} \tag{10}$$

where P_{max} is defined as the MW single contingency, P_{fmin} is the deficit MW power that makes frequency drop from nominal frequency (f_o) to minimum frequency (f_{min}). In our study case, (f_o) and f_{min} are 60Hz and 59.2Hz, respectively.

From (1), the deficit MW power P_{fmin} can be calculated as follows,

$$P_{fmin} = \frac{(f_o - f_{min})(D \times R + K_m)}{R \times (1 + ae^{-\zeta\omega_n t_z} \sin \omega_r t_z + \varphi)} \tag{11}$$

where t_z is the time duration of frequency decline when frequency reaches f_{min}. t_z can be calculated as follows.

$$t_z = \frac{n\pi - \varphi_1}{\omega_r} = \frac{1}{\omega_r} \arctan(\frac{\omega_r T_R}{\zeta\omega_r T_R - 1}) \tag{12}$$

Once EDR1 is determined by the planning procedure, the remaining EDR would be allocated as EDR2 whose mission is to bring the declined frequency up to a secure level (59.7 Hz). It is noted that EDR2 can be coordinated with available Fast Spinning Reserves (FSR) to fulfill this task. The required per unit amount of EDR2 and FSR is calculated as follows.

$$EDR2 + FSR = \Delta P_{max} - EDR1 - \frac{(60 - 59.7)}{60}(D + \frac{1}{R}) \tag{13}$$

After restoring frequency back to 59.7 Hz, the least remaining reserve, which is called Slow Spinning Reserve (SSR), to be planned for continuously returning frequency back to 60Hz is calculated as follows.

$$SSR = \Delta P_{max} - (EDR1 + EDR2 + FSR) \tag{14}$$

Units participating SSR could be slower response spinning units, or fast start turbines.

IV. Execution of the Proposed Frequency Restoration Scheme

If the magnitude of system disturbance is quickly estimated, appropriate EDR could be executed to bring the declined frequency back to the expected level. Once EDR1 is determined by the planning procedure, the remaining demand response would be allocated as EDR2 to bring back the frequency up to a secure level. Detail of the EDR execution procedure is described as follows.

A. Determine the disturbance magnitude

When a sudden frequency drop is detected by the PMU, the system control center would instantly calculate initial rate of the frequency decline, this value is used to calculate the magnitude of system disturbance (P_{step}) as of (9).

B. Decision making for triggering EDR1 or EDR2

1) Moment of EDR1 execution: Once P_{step} is obtained, P_{step} is compared with P_{fmin}. If $P_{step} > P_{fmin}$, it means the contingency amount could drag frequency below f_{min} (59.2Hz). Therefore, EDR1 is initiated. Otherwise, the step is passed to option B. After the execution of EDR1, the renewed power deficit is calculated using the following equation,

$$P_{renew} = P_{step} - EDR1 \tag{15}$$

2) Moment of EDR2 execution: In this option, the corresponding MW power difference (P_{fmin2}) between the frequency f_o and f_{min2} is calculated. The calculation of (P_{fmin2}) is the same as (11) where the f_{min} is replaced by f_{min2}. In our study case, f_{min2} is chosen at 59.7Hz, which is considered as a secure level so that spinning reserve could have enough time to react for frequency restoration. Once P_{fmin2} is obtained, the MW power that EDR2 is going to be casted in the system is equal to the following relation if option 1 is not executed.

$$EDR2 = P_{step} - P_{fmin2} \tag{16}$$

otherwise

$$EDR2 = P_{renew} - P_{fmin2} \tag{17}$$

Using the above relation, more accurate amount of EDR2 will be allocated for restoring the frequency back to the expected level.

Note that if EDR1 is not utilized in the option A, EDR1 would be then automatically allocated for EDR2. The schematic of the EDR control is depicted in Fig. 3.

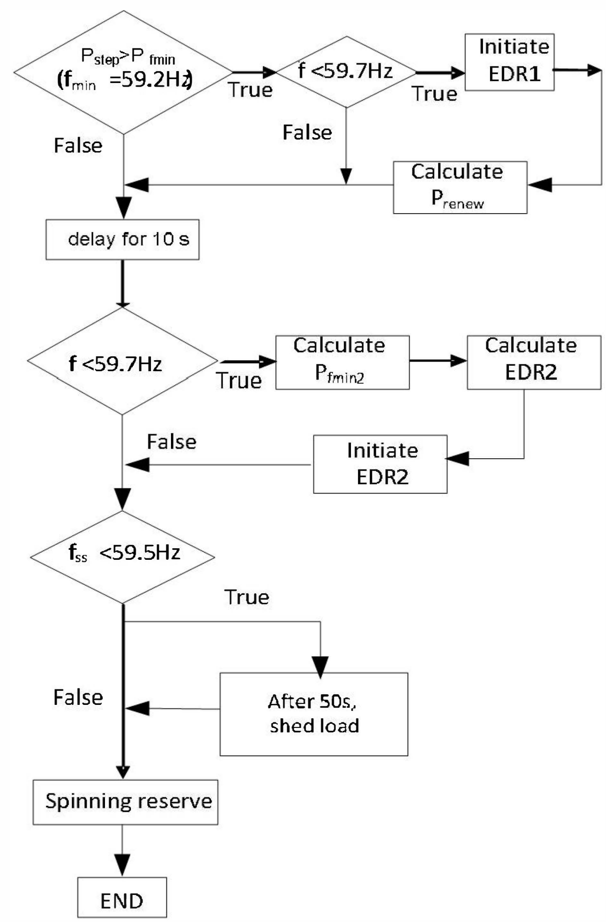

Fig. 3. Schematic of the EDR control for frequency events.

V. Test of the Emergent Demand Response Scheme

In this paper, the adaptive EDR control scheme is tested. Our primary goal is to use EDR1 as the first shedding step to avoid shedding unwanted customer loads at 59.2Hz. Our secondary goal is to allocate sufficient EDR2 so that frequency could be quickly brought back to a secure level (59.7Hz). In order to prove that the EDR plan can fit into various contingency scenarios, we make some tests with different scales of disturbances which were taken by real data sampled from a utility. The simulation will evaluate the performance of the EDR scheme.

A. System Modeling for the Contingency Test

In order to closely simulate the frequency event of a utility, system parameters used in the simulation must be accurate enough to reflect the real frequency trend. The parameters are estimated by the following way: first, collecting the system parameters (such as system droop, load damping, and inertia, etc) and historical frequency response from a utility. After that, we try to make the frequency response of the SFR model as close as possible to the historical record. The estimated parameters are then confirmed to be used for simulations.

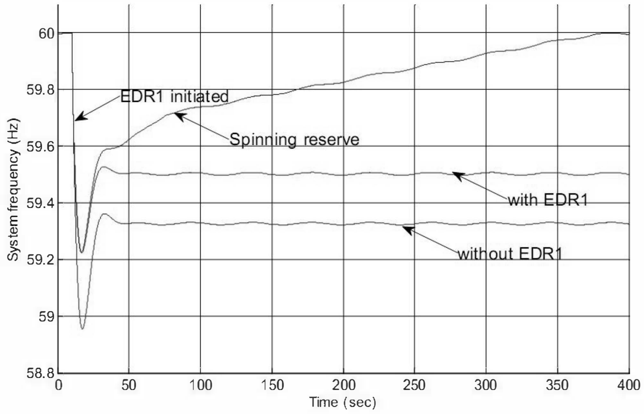

Fig. 4. Simulated frequency curves of scenario 1.

B. Scenario 1: The most severe disturbance

In this scenario, the utility is assumed to have 500MW demand response. When the power system is operating at 25000 MW demand, a maximum single contingency (1900MW) disturbance occurs at f = 60 Hz. The estimated minimum system frequency value would be below 59 Hz.

According to (10), the amount of EDR1 was planned to deal with the maximum single contingency in the system is 472.5MW. As a result, the 500MW demand response is allocated as EDR1. The frequency response curves are shown in Fig. 4 and the decision process of the EDR is shown in Fig. 5.

Fig. 4 shows that when a disturbance occurs without the support of EDR1, the frequency could be down below 59.2 Hz. When the frequency drops below 59.7Hz, EDR1 is initiated. After using the EDR1, the frequency dip is raised above 59.2 Hz and then settled above 59.5Hz. Following the response of EDR1, the spinning reserve continues to restore the frequency back to 60 Hz within 5 minutes.

C. Scenario 2: Medium disturbance

In this scenario, it is assumed that the system has 500MW demand response. When the power system is operating at 20200 MW demand, a single contingency (1100MW) disturbance occurs at f = 60 Hz.

Because the amount of the disturbance is not large enough to make the frequency decline below 59.2Hz, it does not need to initiate EDR1. Following that, the execution process is passed to option 2. According to (13), 500MW EDR2 is sufficient to raise frequency up to 59.7 Hz secure level. After the activation of EDR2, spinning reserve follows to restore the frequency back to 60Hz. Simulated frequency curves and the EDR execution process are shown in Fig. 6 and 7.

D. Scenario 3: Small disturbance

In this scenario, it is assumed that the system has 500MW demand response. When the power system is operating at 21500 MW demand, a single contingency (650MW) unit trip occurs at f = 60 Hz. Because the amount of disturbance is small, the estimated steady state frequency drop is still above

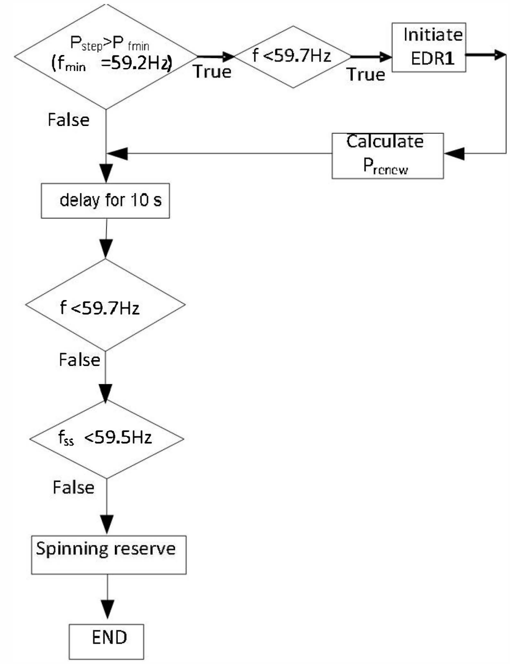

Fig. 5. EDR execution flow chart of scenario 1.

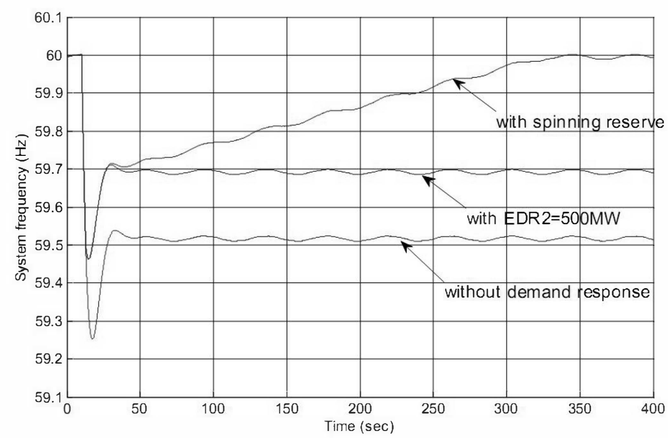

Fig. 6. Simulated frequency curves of scenario 2.

59.7 Hz. Thus, we just need to use the spinning reserve to restore the frequency back to 60 Hz. The frequency curves are shown in Fig. 8.

VI. Conclusion

For frequency security concern, power system operation should be able to perform high reliability by means of automatic control when the system encounters contingent events. Therefore, how to design and execute a suitable frequency restoration plan for the power system has become an important topic. This paper proposes a new adaptive demand response scheme to achieve this goal.

A linear system frequency response (SFR) model is adopted to calculate the amount of system disturbance by means of measuring the system frequency through PMU. Surveys of the estimated magnitude of the disturbance have proven the

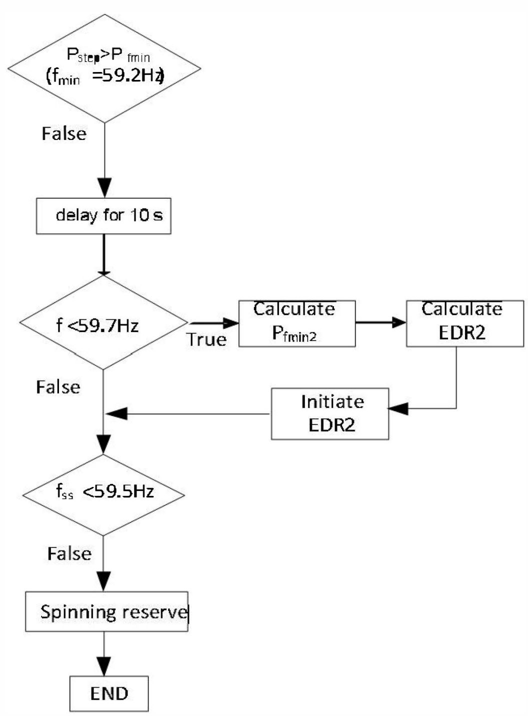

Fig. 7. EDR execution flow chart of scenario 2.

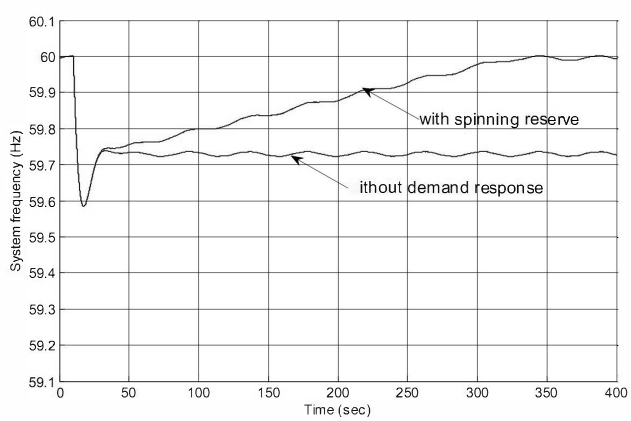

Fig. 8. Simulated frequency curves of scenario 3.

estimation fidelity of high accuracy for calculating the required demand response.

An adaptive emergency demand response plan is introduced to cope with the spinning reserve for restoring the frequency. The effectiveness of the proposed operation is verified by simulations using historical data from a utility. Testing results have confirmed the performance of the proposed scheme to ensure a more reliable power system operation.

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