A Method for the Frequency Security Level Grading of Power System Operation

Cuicui Jin, Liu Liu, Weidong Li, Xiaomeng Li, and Yufei Rao

Abstract—**For the trade-off between the security and economy of power system operation, the control actions such as the preventive control, emergency control, and restorative control, etc. should be selected according to the frequency security level of power system operation. Thus, the theoretical basis for the selection of the control modes of frequency response and the dispatch of the frequency regulation means can be provided. The theoretical research demonstrates that the ratio between the frequency nadir and the quasi-stable state frequency of power system is nearly a constant after disturbance. Moreover, the frequency nadir of power system can be estimated based on the quasi-stable state frequency with the linear regression method of historical data. Hence, the method for the frequency security level grading of power system operation is proposed and the frequency response reserve of generator units and the initial operation frequency of power system, etc. are considered. Because the quasi-stable state frequency involves few parameters and is easy to be calculated, the calculation speed of the frequency nadir is fast and the proposed method can be applied on line. The feasibility and effectiveness of the proposed method are illustrated in the modified New England IEEE 10 generator 39-bus system and the Henan power grid.**

Index Terms—**security and stability control, frequency response, frequency security level grading, constant ratio, linear regression method**

I. INTRODUCTION

With the significant development of the ultra-high voltage (UHV) alternating current (AC) and direct current (DC) hybrid power grid and the annually increasing output power of renewable energy generation, the control problems of active power imbalance in power system become more prominent. Thus, the situation faced by the frequency response (primary frequency) control of power system is extremely severe [1]-[5].

After disturbance, the frequency developing process in power system depends on the contrast between the "attack side" and the "prevention side". Among which, the "attack side" refers to the quantity of the active power imbalance in power system and the "prevention side" refers to the frequency stability control measures before or after disturbance. At present, on the one hand, the conventional generator units are gradually replaced by the renewable energy generation and the amount of them connected to the power grid is significantly decreased. Thus, the system inertia and the frequency response capability of power system are reduced. Furthermore, the capability of power system to deal with the large power loss is decreased. On the other hand, the quantity of the transmission power in UHV AC and DC lines is large and the small-capacity thermal generation units are replaced by the large-capacity ones and the nuclear power units to reduce pollution. Thus, the amount of unbalanced power after a single contingency is dramatically increased in power system. This situation puts forward new requirements and challenges to the security and stability control of system frequency.

In the practical operation of power system, specially after large disturbance, the security and stability control of power system is consist of preventive control, emergency control (It is also known as corrective control, including system inertia, relay protection, frequency response control, under-frequency load shedding, over-frequency generator tripping, and splitting, etc.), and restorative control. These control measures are complementary with each other [6], [7]. Among which, the preventive control includes the operation mode adjustment (the operation or out of service of the frequency regulation means such as generator units, energy storage devices, active load response, and DC power modulation, etc.) and the operation state adjustment (making the system frequency of the sending-end power grid running at the safe upper limit and the receiving-end power grid at the safe lower limit), etc. The purpose is to improve the security and adequacy of the power system which is still in normal operation. The emergency control aims at bringing the operation state of power system back to the normal state after disturbance and mainly contains two parts. One is the frequency stability control measures which can be taken after the occurrence of disturbance, such as the event-driven load-shedding [8] and the active frequency response control [9], etc. They are for the expected transient frequency stability problems and the control mode is the feedforward control which is based on the control idea of off-line analysis and on-line application. The other is the feedback control measures which are based on the local frequency deviations, such as the under-frequency load shedding, over-frequency generator tripping, and splitting, etc. The restorative control is used to restore the system adequacy after the instability of power system. Based on this, whether to put the above control measures into use, the frequency security level of power system operation should be determined after disturbance.

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Thus, the theoretical basis which is for the selection of the frequency response control modes (passive control, active control [9]) and the dispatch of the frequency regulation means, etc. can be provided for the dispatchers.

After disturbance, the frequency security level of power system operation can be directly reflected by the frequency nadir (minimum frequency) of power system. At present, the existing researches mainly focus on the frequency nadir of power system and the dynamic process of frequency response. In [10], with the defined fuzzy index which is consist of seven performance indexes obtained through the full simulation of all credible contingencies, the security level of power system operation can be determined to evaluate the ability of power system to withstand large disturbances. In [11], based on the frequency trajectory obtained from wide-area measurement system or numerical simulations, the cumulative effect of frequency deviations on power equipment is considered. Thus, the frequency security of power system is quantitatively assessed with the frequency security index which is consist of the frequency and time. In [12], with the intelligent framework which is designed for the dynamic security assessment of power systems with large penetration of wind power, the nonlinear relationship between power system parameters and the corresponding security conditions is obtained. Though the frequency security of power system can be assessed with the above researches, the calculation process is complex and the practical application of them is rather difficult. Moreover, the concrete standard which is for the frequency security level grading of power system operation has not been proposed.

For this purpose, the ratio between the frequency nadir and the quasi-stable state frequency of power system operation is studied and thus the frequency nadir of power system can be estimated on line with the linear regression method of historical data. Moreover, a method for the frequency security level grading of power system operation is proposed and the feasibility and effectiveness of the proposed method is illustrated in the modified New England IEEE 10 generator 39-bus system and Henan power grid.

II. Frequency Response Characteristics of Power System

A. Dynamic Process of Frequency Response

After disturbance, the dynamic process of frequency response in power system is shown in Fig.1. Among which, t_A is the time when the disturbance occurs, t_C is the time when the system frequency reaches the frequency nadir, t_B is the time when the system frequency reaches the quasi-stable state frequency, and Δf_{ss} is the quasi-stable state frequency deviation of power system. Moreover, the dynamic process of frequency response can be roughly divided into two stages, the frequency decline stage Δt_{AC} and the frequency recovery stage Δt_{CB}.

It is assumed that the system frequency is greater than the threshold of under-frequency load shedding after disturbance and the frequency response capability of each generator unit keeps constant in the dynamic process of frequency response [13], [14]. In the frequency decline stage, the system frequency keeps decreasing and reaches the frequency nadir at time t_C. During this period, the generator units equipped with governors provide the output power according to the detected local frequency deviation signals. Owing to the time delay from the occurrence of disturbance to exceed the dead band of frequency response, the system frequency keeps reducing and the output power of frequency response is increasing. At time t_C, the quantity of the output power of frequency response is exactly equal to the quantity of power loss. Then, because the output power of frequency response is provided based on the frequency deviation signal at time t_C or that before time t_C, the output power of frequency response continues to increase. Thus, the system frequency starts to rise and then reaches the quasi-stable state frequency of power system at time t_B.

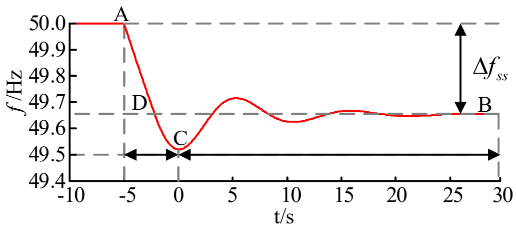

Fig.1 Dynamic process of frequency response.

Based on the energy conservation law, the quantity of the active power imbalance in the “attack side” is equal to that of the output power provided by the “prevention side” in the dynamic process of frequency response. In the frequency decline stage, the output power which is used to balance the power loss can be provided by the system inertia and the output power of frequency response. However, in the frequency recovery stage, the output power is only provided by the output power of frequency response. Because the quantity of the output power of frequency response at both time t_C and time t_B is equal to that of the power loss, the output power of frequency response at time t_C can be approximately considered that the regulation basis is the quasi-stable state frequency deviation Δf_{ss}. Neglect the output power provided by the system inertia during the period which is approaching to time t_C. The regulation basis of the output power of frequency response at time t_C can be regarded as the frequency deviation signal at time t_D. Thus, the response delay of system frequency can be approximately considered as Δt_{CD}.

B. Influencing Factors of Frequency Response

After disturbance, the frequency nadir and the quasi-stable state frequency of power system are the key characteristic parameters which can be used to describe the dynamic process of frequency response and its security or not. Moreover, these parameters are determined by the contrast between the “attack side” and the “prevention side” in the power system.

In the “attack side”, the quantity of the active power imbalance which is caused by the N-1 contingency is increased dramatically in the power system of China [15]. In the “prevention side”, to improve the frequency stability of power system under the situation in which the large-scale renewable energy is connected to the power grid, the frequency control actions before or after disturbance include: 1) the initial system frequency in the sending-end /

receiving-end power grid is adjusted to the safe upper / lower limit. 2) the system inertia, relay protection, and frequency response control, etc. are put into use successively to prevent the frequency decline of power system in the early frequency decline stage. Moreover, if the frequency decline cannot be prevented with the above control measures, the follow-up frequency stability control measures such as the under-frequency load shedding, over-frequency generator tripping, and splitting should be used [16], [17]. 3) the automatic generation control and spinning reserve, etc. are put into use to restore not only the service to the loads but also the adequacy of power system.

III. Frequency Security level grading of Power system

The Chinese State Council Order No.599 [18] specifies that the load shedding of the stability control system is equal to the loss of loads in failure. Thus, the negative effect of the load shedding on the State Grid Corporation of China which is used to maintain the system stability is treated the same as the load which is out of service after disturbance. Hence, the system frequency should be greater than the threshold of the under-frequency load shedding.

After large disturbance, the frequency security level of power system operation depends on the distance from the frequency nadir to the threshold of the under-frequency load shedding. Thus, the frequency nadir of power system can be taken as the basis of the frequency security level grading of power system operation. Furthermore, the control modes of frequency response (passive control, active control [9]) can be selected according to the emergency level of disturbance and the probability of the contingencies (such as the under-frequency load shedding, over-frequency generator tripping, and splitting, etc.) can be reduced.

A. Calculation of the Frequency Nadir

Because the frequency response model is complex and the differential equation solution is involved in the analysis of the dynamic process of frequency response, the online solution of the frequency nadir of power system is difficult. Thus, the mapping relationship between the frequency nadir and the quasi-stable state frequency of power system is studied to estimate the frequency nadir of power system.

1) Frequency Mapping Relationship: The system frequency response (SFR) model which can be used to estimate the frequency behavior of a large power system or islanded portion thereof [19] is shown in Fig.2 and the physical meaning of each parameter is represented in Table Ⅰ.

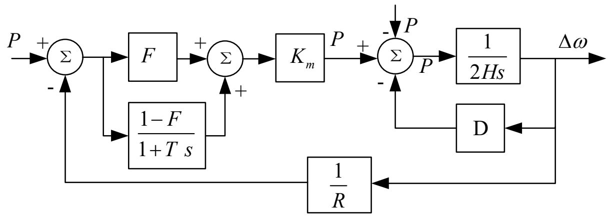

Fig.2 The SFR model.

TABLE I

Physical meanings of parameters in The sfr model

Parameter	Physical Meaning
P_{SP}	incremental power set point, p.u.
P_m	turbine mechanical power, p.u.
P_e	generator electrical load power, p.u.
P_a	accelerating power, p.u.
$\Delta\omega$	incremental rotational speed, p.u.
F_H	fraction of total power generated by the high-pressure turbine
T_R	reheat time constant, s
H	inertia constant, s
D	damping factor
R	frequency regulation coefficient
K_m	mechanical power gain factor

Known from the analysis of the SFR model, the analytical expression of system frequency is:

$$\Delta\omega = \frac{R\omega_n^2}{DR+K_m}\cdot\frac{K_m(1+F_H T_R s)P_{SP}-(1+T_R s)P_e}{s^2+2\varsigma\omega_n s+\omega_n^2} \tag{1}$$

where,

$$\omega_n = \left(\frac{DR+K_m}{2HRT_R}\right)^{\frac{1}{2}} \tag{2}$$

$$\varsigma = \left(\frac{2HR+(DR+K_m F_H)T_R}{2(DR+K_m)}\right)\omega_n \tag{3}$$

If P_{sp}=0, the system frequency under the step disturbance P_{step} satisfies:

$$\Delta\omega = \frac{R\omega_n^2}{DR+K_m}\cdot\frac{(1+T_R s)P_{step}}{s(s^2+2\varsigma\omega_n s+\omega_n^2)} \tag{4}$$

Thus, the time-domain expression of the system frequency is:

$$\Delta\omega(t) = \frac{RP_{step}}{DR+K_m}\left[1+\alpha e^{-\varsigma\omega_n t}\sin(\omega_r t+\phi)\right] \tag{5}$$

where,

$$\alpha = \sqrt{\frac{1-2T_R\varsigma\omega_n+T_R^2\omega_n^2}{1-\varsigma^2}} \tag{6}$$

$$\omega_r = \omega_n\sqrt{1-\varsigma^2} \tag{7}$$

$$\phi = \phi_1 - \phi_2 = \tan^{-1}\left(\frac{\omega_r T_R}{1-\varsigma\omega_n T_R}\right) - \tan^{-1}\left(\frac{\sqrt{1-\varsigma^2}}{-\varsigma}\right) \tag{8}$$

Because the time when the system frequency reaches the frequency nadir can be obtained by solving the differential equation $\frac{d\Delta\omega(t)}{dt}=0$, its expression is:

$$t_z = \frac{1}{\omega_r}\tan^{-1}\left(\frac{\omega_r T_R}{\varsigma\omega_n T_R - 1}\right) \tag{9}$$

Thus, the maximum frequency deviation of power system is:

$$\Delta\omega_C = \frac{RP_{step}}{DR+K_m}\left(1+ \alpha e^{-\frac{\varsigma\omega_n}{\omega_r}\tan^{-1}\left(\frac{\omega_r T_R}{\varsigma\omega_n T_R-1}\right)}\sin\left(\tan^{-1}\left(\frac{\omega_r T_R}{\varsigma\omega_n T_R-1}\right)+\phi\right)\right) \tag{10}$$

The quasi-stable state frequency deviation of power system is:

$$\Delta\omega_B = \frac{RP_{step}}{K_m+DR} \tag{11}$$

Furthermore, the ratio between the maximum frequency deviation $\Delta\omega_C$ and the quasi-stable state frequency deviation

$\Delta\omega_B$ is:

$$\lambda_{CB}=\frac{\Delta\omega_C}{\Delta\omega_B}=1+ \alpha e^{-\frac{\varsigma\omega_n}{\omega_r}\tan^{-1}(\frac{\omega_r T_R}{\varsigma\omega_n T_R-1})}\sin(\tan^{-1}(\frac{\omega_r T_R}{\varsigma\omega_n T_R-1})+\phi) \quad (12)$$

As can be seen from (12), the ratio λ_{CB} is related to the parameters such as ς, ω_n, ω_r, T_R, and Φ, etc. Moreover, the above parameters depend on the operation mode of power system and are affected by the system inertia, the load damping, the inherent characteristics of generator units, and the number of online generator units, etc. Under the premise that the operation mode of power system remains unchanged, the ratio between the maximum frequency deviation and the quasi-stable state frequency deviation of power system is constant.

Based on this, the relationship among the initial operation frequency f_A, the frequency nadir f_C, and the quasi-stable state frequency of power system f_B satisfies:

$$\lambda_{CB}=\frac{f_A-f_C}{f_A-f_B}=\frac{\Delta f_{\max}}{\Delta f_{ss}} \quad (13)$$

where, $\Delta f_{\max}$ is the maximum frequency deviation of power system. Thus, the frequency nadir of power system satisfies:

$$f_c=f_A-\lambda_{CB}\bullet\Delta f_{ss} \quad (14)$$

In the 2015 frequency response annual analysis of North American Electric Reliability Corporation [20], the statistical analysis of the frequency disturbance data in North American shows that the ratio between the frequency nadir and the quasi-stable state frequency of power system is nearly a constant. Thus, the above approximate constant ratio can be validated from the perspective of the practical operation of power system.

2) Calculation of the Quasi-stable State Frequency: In the calculation of the quasi-stable state frequency, the influencing factors of frequency response are analyzed and the frequency response of each generation unit is on-line monitored. Firstly, the inherent characteristic parameters (such as the maximum output power and the frequency regulation coefficient, etc.) of each generator unit are off-line determined. Then, in the practical operation of power system, the actual output power of each generator unit, the number of gird-connected generator units, and the initial system frequency, etc. are collected in real time with the wide-area measurement system [21], [22]. Thus, the quantity of the active power imbalance can be obtained through the on-line monitoring of frequency response [9] on the large-capacity elements (such as the UHV DC transmission lines and the large-capacity thermal and nuclear power units, etc.).

After disturbance, the active power balance of power system satisfies:

$$\Delta P_{\mathrm{L}}=\sum_{j=1}^{N_{\mathrm{G}}}\Delta P_{\mathrm{G},j} \quad (15)$$

$$\Delta P_{\mathrm{G},j}=\begin{cases}\frac{1}{R_j}\Delta f_{\mathrm{ss}} & \frac{1}{R_j}\Delta f_{\mathrm{ss}}\le\Delta P_{\mathrm{up},j}\\ \Delta P_{\mathrm{up},j} & \frac{1}{R_j}\Delta f_{\mathrm{ss}}>\Delta P_{\mathrm{up},j}\end{cases} \quad (16)$$

$$\Delta P_{\mathrm{up},j}=P_{\max,j}-P_j \quad (17)$$

where, ΔP_{L} is the quantity of the active power imbalance, N_{G} is the number of the grid-connected generator units, $\Delta P_{\mathrm{G},j}$ is the output power of frequency response of the jth generator unit, R_j is the frequency regulation coefficient of the jth generator unit, $\Delta P_{\mathrm{up},j}$ is the frequency response reserve of the jth generator unit, $P_{\max,j}$ is the maximum output power of the jth generator unit, and P_j is the actual output power of the jth generator unit.

3) Calculation of the Frequency Nadir: Based on the statistical analysis of the existing frequency disturbance data of power system, the ratio between the frequency nadir and the quasi-stable state frequency of power system can be calculated with the linear regression method of historical data.

Define the sum of the mean square error (*SSE*) as:

$$SSE=\sum_{i=1}^{n}(y_i-\hat{y}_i)^2 \quad (18)$$

where, y_i is the measured data, $\hat{y}_i=ax_i$ is the fitting data, and n is the number of the data sample.

Thus, the minimum *SSE* of fitting data can be obtained by solving:

$$\frac{\partial}{\partial a}SSE=-2\sum_{i=1}^{n}(x_iy_i-ax_i^2)=0 \quad (19)$$

and the ratio between the frequency nadir and the quasi-stable state frequency of power system satisfies:

$$\lambda_{CB}=a=(\sum_{i=1}^{n}x_iy_i)/(\sum_{i=1}^{n}x_i^2) \quad (20)$$

Hence, based on the linear regression method of historical data (18)-(20), the ratio between the frequency nadir and the quasi-stable state frequency of power system can be obtained. Thus, the frequency nadir can be calculated out with the quasi-stable state frequency of power system.

B. Frequency Security Level Grading Standard

Under large disturbance, the frequency response capability of power system is affected by the system scale, grid structure, and the operation mode, etc., and thus the power loss that the power system can endure is not the same. (The disturbance which can cause the under-frequency load shedding of power system is not the same.). Moreover, the frequency deviations of different power systems under the same quantity of active power imbalance are not the same [23]. The smaller the system inertia is, the worse the anti-disturbance capability of power system is. It makes that the risk of the frequency security and stability control problems is greater. Hence, in the frequency security level grading of power system operation, the frequency nadirs under different disturbances can be determined and analyzed based on the historical disturbance data of power system. Thus, the number of the frequency security levels and the corresponding frequency thresholds can be obtained based on the operation requirements of the specific power system.

Because the threshold of under-frequency load shedding is generally set to 49.5Hz in the power system of China, the safe lower limit of system frequency is set to 49.5Hz and it is regarded as the threshold of the last frequency security level. Meanwhile, based on the national standard of the power system in China, the rated frequency is 50Hz and the normal frequency range is ±0.2Hz. Thus, the threshold of the first frequency security level is set to 49.8Hz. Then, to improve the universality of the method for the frequency security level grading of power system operation, the grading standard which is established according to the minimum allowable frequency of power system at current frequency security level (The threshold of the current frequency security level is the minimum allowable frequency of the current frequency security level.) is shown in Table Ⅱ. Among them, $f_{\text{threshold}}$ represents the threshold of the current frequency security level.

After the frequency security level grading of power system operation, the configuration requirements of the frequency response capability of power system can be determined in the current frequency security level. Thus, the theoretical guidance can be provided for the coordination and optimizing allocation of the frequency regulation means.

TABLE Ⅱ
FREQUENCY SECURITY LEVEL GRADING STANDARD

Frequency Security Level	$f_{\text{threshold}}$ (Hz)
Ⅰ	49.8
Ⅱ	49.7
Ⅲ	49.6
Ⅳ	49.5

C. Calculation Procedure

After large disturbance, for the specific power system, the frequency security level grading of power system operation and the calculation procedure of the practical frequency response capability of power system are shown in Fig.3.

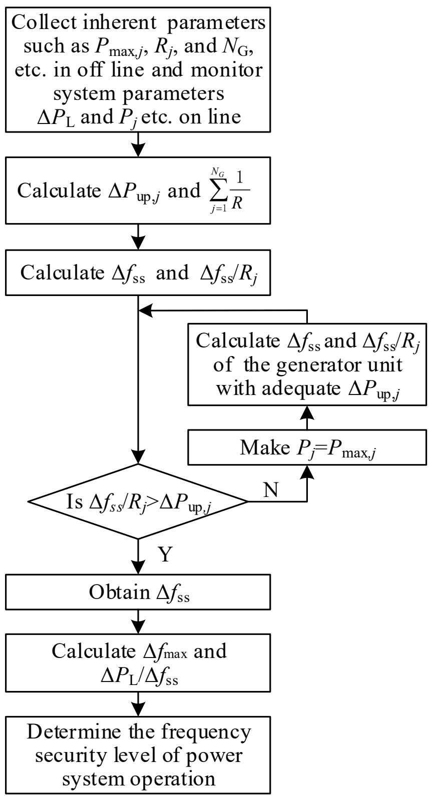

Fig.3 Flow-chart of the frequency security level grading of power system operation.

The proposed method can be summarized into the following steps:

Step 1: The inherent characteristic parameters of the generator units in power system is off-line collected and the frequency response of power system is on-line monitored.
Step 2: The frequency response reserve and the total frequency response capability of power system are calculated.
Step 3: The average quasi-stable state frequency deviation of power system and the corresponding output power increment of each generator unit are calculated.
Step 4: The calculated output power increment of each generator unit is compared with the frequency response reserve of the corresponding generator unit.
Step 5: If the frequency response reserve of each generator unit is adequate, the quasi-stable state frequency deviation can be obtained. Otherwise, the output power of the generator units in which the frequency response reserve is inadequate should be set to the maximum and the remaining active power imbalance is allocated to the remaining generator units. Then, repeat the above procedures.
Step 6: The ratio between the frequency nadir and the quasi-stable state frequency of power system operation is obtained and thus the frequency nadir and the practical frequency response capability of power system are calculated.
Step 7: The frequency security level of power system operation is determined.

IV. CASE STUDY

The proposed method for the frequency security level grading of power system operation is applied to the modified New England IEEE 10 generator 39-bus system and Henan power grid which is a real provincial power system in Central China.

A. Modified New England IEEE 10 Generator 39-Bus System

The modified New England IEEE 10 generator 39-bus system is consist of ten generator units and the parameters are shown in Table Ⅲ. The frequency fluctuation of the test system is simulated with the collected frequency data of a practical power system in China. Moreover, the ratio between the frequency nadir and the quasi-stable state frequency of the test system is obtained with the existing frequency disturbance data of the practical power system. It is assumed that the normal frequency range is ±0.2Hz and the rated frequency and the threshold of the under-frequency load shedding are 50Hz and 49.5Hz respectively.

TABLE Ⅲ
PARAMETER INFORMATION OF GENERATOR UNITS

Bus Number	Type of Generator	σ (%)	P_G (MW)	S_N (MW)	ΔP_{UP} (MW)
30	hydropower	3.5	250	800	550
31	thermal power	4.0	678	1000	322
32	hydropower	3.0	650	800	150
33	thermal power	4.0	632	750	118
34	thermal power	5.0	508	750	242
35	thermal power	4.5	650	750	100
36	thermal power	5.0	560	750	190
37	thermal power	4.5	540	660	120
38	thermal power	4.5	830	1000	170
39	thermal power	5.0	1000	1100	100

Based on the collected frequency data of the practical power system, the probability density function (PDF) and the cumulative distribution function (CDF) of the frequency distribution in the modified New England IEEE 10 generator 39-bus system are shown in Fig.4.

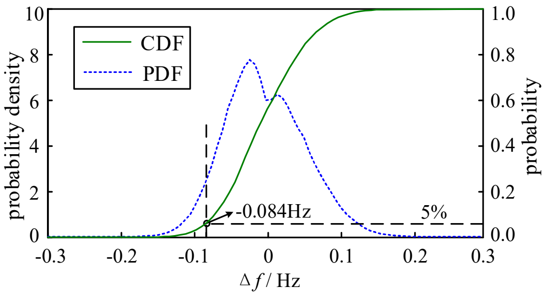

Fig.4 PDF & CDF of frequency.

As shown in Fig.4, the system frequency presents an approximate normal distribution and the confidence intervals can be determined according to the principle of 3σ. Thus, the system frequency under different confidence levels can be shown in Table Ⅳ and the lower limit of the normal system frequency should be 50-0.084Hz to ensure 95% confidence level.

TABLE Ⅳ LOWER LIMIT OF THE SYSTEM FREQUENCY UNDER DIFFERENT CONFIDENCE LEVELS

Confidence Level	Frequency (Hz)
95%	49.916
97%	49.906
98%	49.886

Then, based on the existing frequency disturbance data, the ratio between the frequency nadir and the quasi-stable state frequency can be obtained with the linear regression method (18)-(20) and the fitting result is shown in Fig.5. Thus, the value of the ratio λ_{CB} is 1.2904.

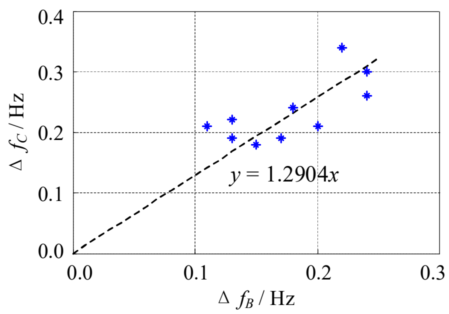

Fig.5 Calculation of the frequency ratio.

As shown in Table Ⅲ, the largest capacity of the single generator unit in the modified New England IEEE 10 generator 39-bus system is 1100MW. Consider the frequency stability of the system under the N-1 contingency (The thermal power unit which is connected to the bus 39 is out of service.) and thus the frequency security level of power system operation is graded according to the maximum allowable frequency deviation under the current frequency security level. Moreover, the corresponding frequency response capability of the system can be determined. The specific frequency security level grading standard of power system operation is shown in Table Ⅴ.

TABLE Ⅴ FREQUENCY SECURITY LEVEL GRADING STANDARD OF THE MODIFIED NEW ENGLAND IEEE 10 GENERATOR 39-BUS SYSTEM

Frequency Security Level	$f_{threshold}$ (Hz)	Δf_{max} (Hz)	Δf_{ss} (Hz)	β_{min} (MW/HZ)
Ⅰ	49.8	0.116	0.089	12360
Ⅱ	49.7	0.216	0.167	6587
Ⅲ	49.6	0.316	0.245	4490
Ⅳ	49.5	0.416	0.322	3416

Under the N-1 contingency, the quasi-stable state frequency deviation and the total frequency response capability of the modified New England IEEE 10 generator 39-bus system can be on-line calculated and then compared with the frequency thresholds in Table Ⅴ. Thus, the frequency security level of power system operation can be determined in real time. The specific calculation procedure of the frequency security level grading is shown in Fig.6.

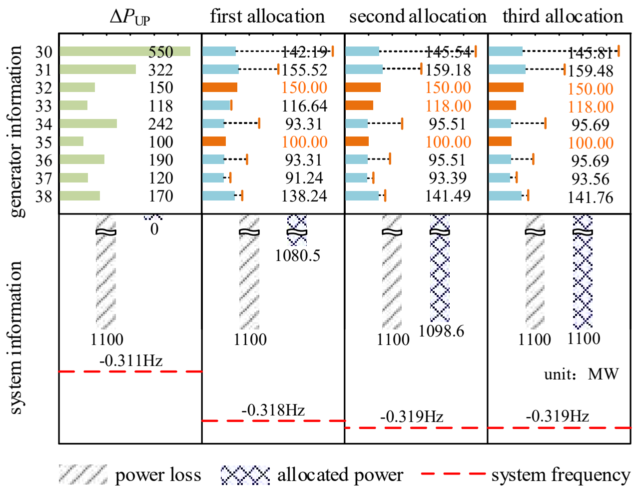

Fig.6 Calculation procedure of the modified New England IEEE 10 generator 39-bus system.

As shown in Fig.6, in the first allocation of the power loss, the quantity of the active power imbalance is distributed to each generator unit according to the frequency regulation coefficient of each generator unit. Thus, the calculated quasi-stable state frequency deviation of the modified New England IEEE 10 generator 39-bus system is -0.318Hz and the quantity of the remaining active power imbalance is 19.5MW. Among them, the output power of the generator units connected to the bus 32 and 35 has already reached the maximum. In the second allocation, the remaining active power imbalance is allocated to the generator units whose frequency response reserve is still adequate. Thus, the calculated quasi-stable state frequency deviation is -0.319Hz and the quantity of the remaining active power imbalance is 1.4MW. Moreover, the output power of the generator unit connected to bus 33 has also reached the maximum. Then, in the third allocation, the active power imbalance is completely allocated to the generator units in which the frequency response reserve is adequate. Thus, the active power balance of the modified New England IEEE 10 generator 39-bus system is achieved and the quasi-stable state frequency deviation is -0.319Hz. The allocation of the active power imbalance among the generator units in the test system is stopped.

Hence, the maximum frequency deviation of the modified New England IEEE 10 generator 39-bus system satisfies:

$$\Delta f_{max,3} \le \Delta f_{max} = 0.319*1.2904 \approx 0.412 \text{ Hz} \le \Delta f_{max,4}$$

and its frequency response capability meets:

$$\beta_{min,3} \le \beta = 1100 / 0.319 \approx 3448 \text{ MW/Hz} \le \beta_{min,4}$$

Furthermore, the frequency security level of the modified New England IEEE 10 generator 39-bus system can be determined according to the above calculation results and its frequency security level of power system operation is Ⅳ.

B. Henan Power Grid

Henan power grid is a practical power system in Central China with the total installed capacity of 73234MW and the nominal frequency response capability of 30727MW/Hz. To pursue the economic benefits one-sidedly, most of the generator units in Henan power grid are nearly in full load operation and thus the frequency response reserve is insufficient. Because Henan power grid is a receiving-end power grid of several UHV DC transmission lines, the frequency security and stability of Henan power grid especially in low load mode is increasingly serious.

With the collected frequency data of Henan power grid in 2018, the lower limit of the normal system frequency of Henan power grid should be 50-0.087Hz to ensure 95% confidence level of system frequency. Moreover, based on the historical disturbance data and the linear regression method (18)-(20), the ratio between the frequency nadir and the quasi-stable state frequency of Henan power grid can be obtained and it should be 1.3941.

At present, the most serious N-1 contingency in Henan power grid is the DC bipolar blocking fault of UHV transmission lines from Tianshan to Zhongzhou and the quantity of the power loss is 3350MW. Under the N-1 contingency, the specific frequency security level grading standard of power system operation is shown in Table Ⅵ.

TABLE Ⅵ
FREQUENCY SECURITY LEVEL GRADING STANDARD OF HENAN POWER GRID

Frequency Security Level	$f_{threshold}$ (Hz)	Δf_{max} (Hz)	Δf_{ss} (Hz)	β_{min} (MW/HZ)
Ⅰ	49.8	0.113	0.081	41330
Ⅱ	49.7	0.213	0.153	21926
Ⅲ	49.6	0.313	0.225	14921
Ⅳ	49.5	0.413	0.296	11308

In the low load mode, the frequency response reserve of each generator unit in Henan power grid is quite little and the value of the practical frequency response capability is much less than the nominal value. Take the same approach as that of the modified New England IEEE 10 generator 39-bus system and thus the power loss is distributed to each generator unit according to the frequency regulation coefficient. After six allocations, the allocation of the power loss is stopped and the quasi-stable state frequency deviation is -0.320Hz.

Hence, the maximum frequency deviation of Henan power grid satisfies:

$$\Delta f_{max} = 0.320*1.3941 \approx 0.446 \text{ Hz} > \Delta f_{max,4}$$

and its frequency response capability meets:

$$\beta = 3350 / 0.320 \approx 10469 \text{ MW/Hz} < \beta_{min,4}$$

Know from the above calculation results, the frequency nadir of henan power grid is lower than the threshold of under-frequency load-shedding and thus the transient stability of Henan Power grid will be destroyed under the N-1 contingency. To ensure the security and stability of Henan power grid, more frequency stability control measures should be taken into use and more generation management methods for the generator units should be studied in the follow-up work.

V. CONCLUSION

The proposed method for the frequency security level grading of power system operation can determine the frequency security level of power system on line and provide the theoretical basis for the selection of the control modes of frequency response and the dispatch of the frequency regulation means.

After disturbance, the ratio between the frequency nadir and the quasi-stable state frequency of power system is nearly a constant. Thus, based on the current quasi-stable state frequency which is obtained through the on-line monitoring of frequency response, the frequency security level and the practical frequency response capability of power system can be determined in real time. Moreover, because the quasi-stable state frequency of power system involves less parameters and its calculating speed is fast, the proposed method is practical and can be used on line.

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