

PAPER • OPEN ACCESS

Optimization model of high-frequency second defense line of generator tripping based on frequency safety constraints

To cite this article: Lin Hengxian *et al* 2020 *IOP Conf. Ser.: Earth Environ. Sci.* **512** 012108

View the [article online](#) for updates and enhancements.

You may also like

- [Correlation between single-wire and multi-wire tripping of the flow past a circular cylinder](#)
Antrix Joshi and Ali Ekmekci
- [Topologically protected loop flows in high voltage AC power grids](#)
T Coletta, R Delabays, I Adagideli et al.
- [Discussion on the Over-frequency Generator Tripping Scheme of the Power Grid](#)
Yiting Guo, Haipeng Nan, Xin Guan et al.



ECS
The
Electrochemical
Society
Advancing solid state &
electrochemical science & technology

DISCOVER
how sustainability
intersects with
electrochemistry & solid
state science research

Optimization model of high-frequency second defense line of generator tripping based on frequency safety constraints

LinHengxian¹, HouKaiyuan², Chen Lei^{1*}, XiaDeming², MinYong¹, Qin Shuang², Zhang Bowen²,

¹State Key Lab of Power Systems, Department of Electrical Engineering, Tsinghua University, Beijing, Beijing, 100084, China

²Northeast Branch of State Grid Corporation of China, Shenyang, Liaoning Province 110180, China

*Corresponding author's e-mail: chenlei08@mail.tsinghua.edu.cn

Abstract. Once the transmission grid of the external UHVDC transmission system has a blocking fault, it will cause high-frequency problems. The adjustment capacity of the system alone often cannot meet the requirements, and the generators need to be tripped in the second defense line of the grid. However, the current tripping method of the high-frequency second line of defense is not systematic. This paper first proposes a simple and practical frequency safety constraint condition. When the system meets the constraint condition, the maximum frequency deviation under a given power disturbance will remain within the set limit. At the same time, based on this constraint condition, a generator tripping optimization model of the high-frequency second line of defense is proposed. The simulation results prove that the tripping solution obtained by solving the model can make the highest frequency and steady state frequency of the system meet the setting requirements, meanwhile, it can reduce the tripping amount and avoid excessive generator tripping.

1. Introduction

Frequency is one of the key indicators of grid operation. For a long time, with the increase of the interconnection scale of the power grid, the power grid's ability to resist power disturbances has been continuously improved, and the frequency security problem has not been prominent. However, with the large number of applications of DC transmission in China, DC transmission, especially UHVDC transmission, has a large design capacity, and once a DC blocking fault occurs, it will bring a huge power shock to the system. Taking the Northeast China Power Grid as an example, a high proportion of wind power systems transmit power through UHVDC, once DC blocking occurs, it will cause serious high-frequency problems.

China's power grid has three lines of defense [1]. Usually, the high-frequency problems caused by DC blocking will be dealt with by the second and third lines of defense. The operation of the high-frequency third line of defense is generally a high-frequency generator trip, which tripping operation is divided into rounds according to different frequency settings, and it is a phenomenon drive. The second line of defense is accident-driven, and the corresponding actions are arranged according to the events that may occur in the power grid. A lot of literatures on the third line of defense of high frequency have been studied in China [2-5]. For the high-frequency second line of defense against DC



blocking in the DC delivery system, most studies are still at the stage of configuring corresponding operations based on empirical values [6-8].

One of the main principles for setting the second high-frequency line of defense is that the maximum deviation of the frequency is less than the set limit, but the calculation of the maximum deviation is often complicated. Traditional methods for calculating the maximum frequency deviation have time-domain simulation methods [9-11], intelligent algorithms [12,13], and analytical methods [14,15]. The time-domain simulation method needs to build a complex simulation model of the system, and the solution efficiency is not high; the intelligent algorithm does not need a known model structure and parameters. It is a type of sample-based prediction method that requires a large number of samples to learn. However, both can only find the numerical solution of the maximum frequency difference, which cannot be expressed analytically, and it is not convenient to apply it to the generator trip setting scheme. And the traditional analytical method for calculating the maximum frequency deviation is often highly nonlinear and difficult to apply.

In view of the above problems, this paper presents a optimization model of high-frequency second defense line of generator tripping based on frequency safety constraints. The remaining part of the paper is organized as follows. In section 2 a dynamic frequency safety constraint condition is proposed, and when the system meets this condition, the maximum frequency deviation after the system is disturbed is less than the set limit. The frequency security constraint expression is more practical and concise. At the same time, the constraint condition is conservative, which can guarantee system security. Then, in section 3 a high-frequency second-line defensive generator tripping optimization model based on the above-mentioned frequency safety constraint conditions is proposed. This model can guarantee the minimum tripping capacity under the premise of frequency safety. Finally, in section 4 an IEEE 10-units 39-node system is used for testing, which proves the effectiveness of this method.

2. Dynamic frequency safety constraints in power systems

The frequency dynamic process of the power system refers to the process of the system frequency transitioning from a normal steady state value to a new frequency steady state value (or loss of stability, system frequency collapse) after power disturbances such as generator trips, load increases and decreases. First, the high frequency problem is taken as an example to analyse the dynamic process of frequency.

The typical frequency dynamic characteristics during the frequency rise are shown in figure 1:

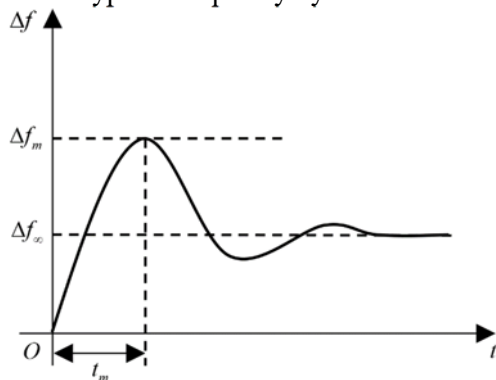


Figure 1. Dynamic frequency characteristics of power system

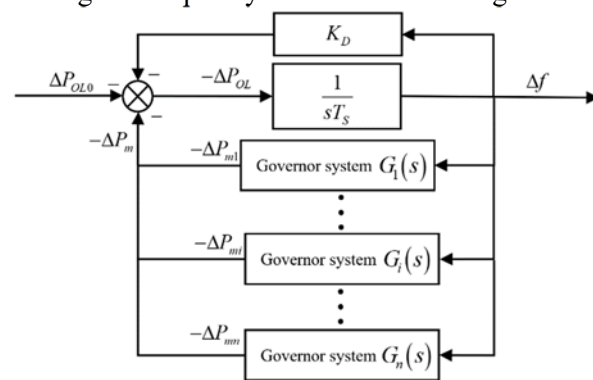


Figure 2. Dynamic frequency response model of the system

In the frequency dynamic process of the power system, the frequencies measured by each bus in the system will exhibit different spatial and temporal distribution characteristics. If the influence of the network structure is ignored and the dynamic characteristics of the governor are retained, an average system frequency (ASF) model as shown in figure 2 can be established.

The dynamic process of system frequency can be described by the following equation:

$$\Delta P_{OL0} - \Delta P_m + T_s \frac{d\Delta f}{dt} + k_D \Delta f = 0 \quad (1)$$

Where, ΔP_{OL0} is the power disturbance, T_s is the total moment of inertia of the system, which is equal to the sum of the moments of inertia of all operating units, k_D is the frequency load adjustment effect coefficient, and ΔP_m is the power absorbed by the generator prime mover governor. The frequency has a maximum rise rate at the moment of disturbance, and its value is $(d\Delta f/dt)|_{t=0} = \Delta P_{OL0}/T_s$.

In the frequency dynamic process after power disturbance, when the value of ΔP_{OL} is zero, the change rate of Δf is zero. At this time, the system frequency just reaches the maximum value. It may be set to $f_0 + \Delta f_m$, that is, the power absorbed by the prime mover system and the load is just the initial power deficit. The frequency deviation of the system reaches the maximum value during equilibrium. Assuming that the time when the system frequency deviation reaches the maximum value is t_m , the power absorbed by the prime mover system and the load at time t_m is exactly equal to the initial power surplus of the system, that is, $\sum_{i=1}^N \Delta P_{mi} + k_D \Delta f_m = \Delta P_{OL0}$. Where, ΔP_{mi} is the power absorbed by the unit i prime mover system, $\sum_{i=1}^N \Delta P_{mi} = \Delta P_m$.

From another perspective, if the system meets the following constraints at time t_m :

$$\sum_{i=1}^N \Delta P_{mi} + k_D \Delta f_m \geq \Delta P_{OL0} \quad (2)$$

Then the system frequency deviation will stop rising before reaching Δf_m , and the maximum frequency deviation of the system will be less than Δf_m . If Δf_m is taken as the maximum frequency deviation limit required by the system, then equation (2) can be used as a constraint condition for system frequency safety. As long as the system satisfies equation (2), it can be ensured that the maximum frequency deviation of the system under power disturbance ΔP_{OL0} is less than Limit Δf_m . In the above constraint equation, how to determine the time t_m of the highest point of the system frequency and the power absorbed by the prime mover system at time t_m becomes the key.

The highest frequency of time t_m is affected by factors such as the inertia of the unit, the governor and prime mover, and the size of the disturbance. The exact expression is very complicated. This section presents an approximate calculation method. Power disturbance instantaneous frequency change rate $(d\Delta f/dt)|_{t=0} = \Delta P_{OL0}/T_s$, as shown in figure 3. The average slope (frequency change rate) from the initial point to the highest point of frequency is set to $k = \delta(d\Delta f/dt)|_{t=0}$, where δ is the ratio of the two slopes. According to the derivation in Appendix, for a sinusoid without attenuation, the value of δ is $2/\pi$; the actual frequency response curve is a sinusoid with attenuation, and the value of δ is less than $2/\pi$. In addition, it is proved from Appendix that the larger the δ , the smaller the adjustment power $\Delta P_m(t)$. Therefore, a larger value of δ can obtain conservative results. Based on the principle of conservatism, the proportionality coefficient δ is taken as $2/\pi$ in this paper. Then t_m can be expressed as:

$$t_m = \frac{\pi T_s \Delta f_m}{2 \Delta P_{OL0}} \quad (3)$$

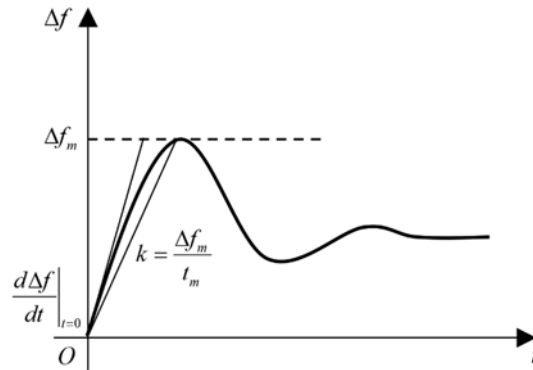


Figure3. System dynamic frequency response characteristics

Next, determine the power adjustment amount ΔP_{mi} of the prime mover system of each generator. It is not difficult to know from figure 2 that $\Delta P_{mi} = -G_i(s) \Delta f(s)$, that there is a close relationship between the power adjustment amount and the frequency change curve and the transfer function of the prime mover system. This section also uses the approximate calculation method. For the unit's prime mover system in figure 2, the simplest can use a first-order inertia link to simulate the dynamic process of the governor [21], as shown in equation (4). For an actual unit, the power-frequency characteristic coefficient K_G and the integrated time constant T_G of the generator governor and the prime mover can be obtained by fitting the step response of the prime mover system by the least square method.

$$G_i(s) = K_G / (1 + sT_G) \quad (4)$$

From the foregoing analysis, it can be known that the expression of Δf is complicated. The straight line from the initial point to the highest frequency point in figure 3 is approximated, and the slope is k . When a straight line approximation is used, the frequency difference obtained by the straight line approximation before t_m is less than the actual frequency difference, and the adjustment power of the prime mover system will be less than the actual value. Using this approximation can also make the result conservative. According to the approximated frequency curve and the first-order simplified model of the prime mover system, the power absorbed by the governor and prime mover can be obtained as:

$$\Delta P_{mi}(t) = -k \cdot K_{Gi} \left(t - T_{Gi} + T_{Gi} e^{-\frac{t}{T_{Gi}}} \right) \quad (5)$$

Where, K_{Gi} and T_{Gi} are respectively the power-frequency characteristic coefficient of unit i and the integrated time constant of the generator governor and prime mover.

Substituting ΔP_m back into the system frequency constraint expression, we get:

$$\frac{2 \Delta P_{OL0}}{\pi T_s} \sum_{i=1}^N K_{Gi} \left[t_m - T_{Gi} + T_{Gi} \cdot e^{-t_m/T_{Gi}} \right] + k_D \Delta f_m \geq \Delta P_{OL0} \quad (6)$$

That is, if the system operating conditions meet the following constraints, when a power disturbance with a power value of ΔP_{OL0} occurs, the maximum frequency deviation value of the system can be guaranteed within the range of Δf_m .

However, equation (6) does not consider the output limitation of the unit, and it will be improved in the next.

It can be known from the frequency safety constraint that the prerequisite for its establishment is that all units and loads at time t_m can reduce the power value with a value greater than or equal to ΔP_{OL0} . In fact, considering the minimum output limitation of the unit, the reduction in the output of the i -th unit may not necessarily reach $2\Delta P_{OL0}K_{Gi} \left[t_m - T_{Gi} + T_{Gi} \cdot e^{-t_m/T_{Gi}} \right] / \pi T_s$. Therefore, the following constraints are added:

$$\Delta P_i = \min \left(\frac{2\Delta P_{OL0}}{\pi T_s} U_i K_i \left[t_m - T_i + T_i \cdot e^{-t_m/T_i} \right], P_i - P_{i\min} \right), \quad \sum_{i=1}^N \Delta P_i + k_D \Delta f_m \geq \Delta P_{OL0} \quad (7)$$

Where $P_{i\min}$ represents the lower output value of unit i . Adding this constraint ensures that the system can provide enough power at time t_m to meet the frequency modulation conditions.

For the steady-state frequency, according to the transfer function expression of the prime mover system, it is not difficult to find the steady-state frequency expression of the system as:

$$\Delta f_\infty = \Delta P_{OL0} / (k_D + \sum K_{Gi}) \quad (8)$$

3. Generator tripping setting of high-frequency second line of defense based on frequency safety constraints

In the previous section, the power system frequency safety constraint expression was derived. In this section, based on this constraint condition, a method of setting the second line of defense of the generator tripping is proposed.

The UHVDC transmission system has a large capacity design. Once a problem such as a blocking fault occurs, the transmitting network will become an island system with a low frequency self-regulating ability. Once such a large power disturbance occurs, the highest value of the frequency will be greater than the safety threshold of the power grid, which may lead to further failures such as grid decommissioning.

According to figure 2, an effective way to reduce the highest value of the frequency is to reduce the power surplus, which corresponds to the operation of the power grid to trip generator. However, the tripping operation will reduce the inertia in the power grid, and the reduction of the unit will also weaken the frequency modulation performance of the system. How to set the tripping amount of the system after a DC fault has become one of the difficulties of the high-frequency second line of defense of the power grid.

At the same time, the frequency modulation capabilities of different units are different. The machine should follow the principle of preferentially tripping the generators with large output value and relatively poor frequency modulation capability. However, the frequency regulation capability of the unit depends on the unit's inertia T_s , the unit's power-frequency characteristic coefficient K_G , and its integrated time constant T_G .

The system's tripping volume is closely related to which unit to trip. The two are coupled with each other and the relationship is extremely complicated. At present, it is not possible to determine a tripping standard that comprehensively considers the output of the unit, the inertia T_s of the unit, the power-frequency characteristic coefficient of the unit K_G and its comprehensive time constant T_G .

Synthesizing the above problems, this paper proposes an optimization model of the second line of defense tripping generators based on the frequency security constraints. The model can solve specific generator tripping schemes for the determined maximum frequency requirements and steady-state value requirements of power disturbance faults.

3.1 Optimization model of high-frequency second defense line of generator tripping based on frequency safety constraints

According to the foregoing analysis, it is known that the system tripping amount and the tripping mode are mutually coupled. This section presents a model that uses an optimized approach to solve the tripping scheme.

3.1.1 Objective function.

The objective function is usually the lowest total trip:

$$\min F = \sum_{i=1}^N V_i P_i \quad (9)$$

In the formula, F is the total tripping amount; P_i is the output value of unit i ; N is the total number of units; i is the i -th unit; V_i is the tripping state of unit i ; $V_i = 1$ means that the unit has performed the tripping operation; $V_i = 0$ means the unit maintains the original state.

3.1.2 Restrictions.

The model must meet the following constraints during the optimization process:

(1) Frequency dynamic constraint

According to the previous analysis, the frequency of the unit after it completes the tripping operation should meet the corresponding frequency limit:

$$\Delta P_i = \min \left(\frac{2\Delta P_{OL}}{\pi T_s} U_i K_i \left[t_m - T_i + T_i \cdot e^{-t_m/T_i} \right], P_i - P_{i\min} \right) \quad (10)$$

$$\sum_{i=1}^N \Delta P_i + k_D \Delta f_m \geq \Delta P_{OL}', \quad \Delta P_{OL}' = \Delta P_{OL0} - \sum_{i=1}^N V_i P_i, \quad U_i = U_{0i} - V_i, \quad U_{0i} \geq V_i$$

In the formula, ΔP_{OL0} is the initial power disturbance value of the system, and Δf_m is the required maximum frequency limit. U_i is the state variable of the unit i after the tripping. U_{0i} is the initial state variable of the unit i . When the state variable = 1, the unit is turned on, and when 0 is the unit is not turned on.

(2) Frequency steady constraint

Considering the dynamic requirements of the system, the steady-state frequency requirements of the system should also be considered:

$$\Delta P_i' = \min(U_i K_{Gi} \Delta f_\infty, P_i - P_{i\min}), \quad \sum_{i=1}^N \Delta P_i' + k_D \Delta f_\infty \geq \Delta P_{OL}' \quad (11)$$

Where Δf_∞ is the required frequency steady state limit.

(3) Power flow constraint

After tripping, the network security constraints of the system must be met, that is, power flow security constraints. Using DC power flow:

$$P_{l,\min} \leq \sum_{i=1}^N G_{l-i} P_i - \sum_{j=1}^{N_l} G_{l-j} P_d \leq P_{l,\max} \quad (12)$$

Where G_{l-i} describes the effect of the injected power of node i on line l . Where, P_i and P_d are the power values of the unit and the load node, respectively. $P_{l,\max}$ and $P_{l,\min}$ are the maximum and small currents that the line can pass, respectively, set here as 10 and -10 p.u.

Solve the above model to get the tripping plan.

3.2 Model solving

The optimization problem is a mixed integer nonlinear programming problem. This paper uses Gurobi solver to solve.

Gurobi cannot solve the nonlinear constraint problem directly. In this problem, the frequency constraint is a highly nonlinear constraint. This section discusses how to linearize it.

Change the frequency safety constraint condition (6) to:

$$\delta \Delta P_{OL0} \sum_{i=1}^N U_i K_i \left[t_m - T_i + T_i \cdot e^{-t_m/T_i} \right] \geq T_s (\Delta P_{OL0} - k_D \Delta f_m) \quad (13)$$

There are three kinds of non-linear expressions: exponential term, binary production and binary-continuous production. min function appears in formula (7). The linearization method of the nonlinear term is as follows:

(1) Exponential term, binary production and binary-continuous production.

The way of linearizing the exponential term can be referred to [20]; and the way of linearizing the binary production and binary-continuous production can be referred to [21].

(2) Linearization of the min function

For $\min(a_1, a_2, \dots, a_n)$, n intermediate binary variables $v_1, v_2, \dots, v_n$ are introduced, and the min function can be expressed using c after adding the following constraints:

$$c = v_1 a_1 + \dots + v_n a_n, \quad \sum v_i = 1, \quad c \leq a_1, \dots, c \leq a_n \quad (14)$$

4. Example analysis

4.1 Frequency safety constraint verification

This section verifies the frequency dynamic security constraints derived in section 2. Randomly generated 1600 five-machine systems, where each unit's T_s , T_G , K_G , k_D parameter range reference [21] is (2,10), (5,11), (16.7,25), (2,10), the unit start-up conditions is also randomly generated. The highest frequencies of the systems that meet the frequency constraint equations and those that do not meet the frequency constraint equations are obtained and compared with the maximum frequency difference limits. At the same time, the power disturbance value of 20MW, 45MW, the maximum frequency deviation limit is 0.65Hz, 1.5Hz, the test, the results can be obtained as follows. The vertical axis in the figure represents the lowest frequency of each system, and the blue horizontal line in the figure represents the maximum frequency deviation limit of the frequency.

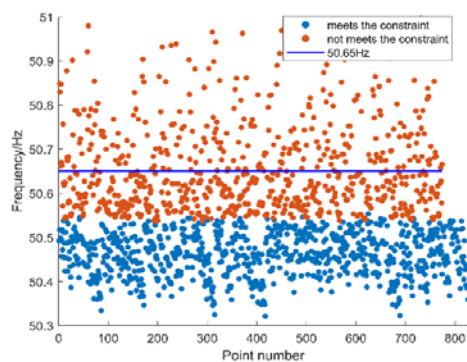


Figure 4. Power disturbance 20MW, the maximum frequency deviation requires 0.65Hz

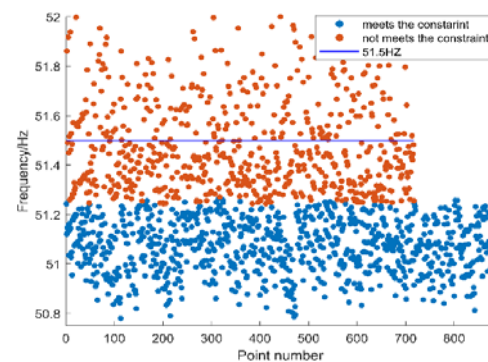


Figure 5. Power disturbance 45MW, maximum frequency deviation 1.5Hz required

It can be seen that all the points (blue dots) representing the maximum frequency difference of the system meeting the frequency constraint equation are below the blue horizontal line, that is, the maximum frequency difference is less than the limit. The red dots represent systems that do not

comply with the constraint equations, and a considerable portion of the maximum frequency difference is not satisfactory. The maximum frequency deviation of a system that satisfies the constraint equation is less than the required limit, and it is conservative.

4.2 Analysis of optimal model of high-frequency second line generator tripping

4.2.1 Solution to the second line of defense optimization generator tripping model

Let the load of node 39 was disconnected, and the power disturbance was 1104MW. Set four frequency requirements respectively: 1. The maximum frequency deviation does not exceed 0.1Hz and the steady state frequency deviation does not exceed 0.05Hz; 2. The maximum frequency deviation does not exceed 0.2Hz and the steady state frequency deviation does not exceed 0.1Hz; 3. The maximum frequency deviation does not more than 0.5Hz, the steady-state frequency difference does not exceed 0.2Hz; 4. The maximum frequency deviation does not exceed 0.7Hz, and the steady-state frequency difference does not exceed 0.3Hz. At the same time, compared with the system without tripping generator operation, the results are as follows:

Table 1. Installed capacity of power grid

Frequency requirement	Tripping amount / MW	Tripping number	Maximum frequency / Hz	Minimum frequency / Hz	Maximum frequency requirement / Hz	Minimum frequency requirement / Hz
Requirement1	1048	5,8	50.0454	50.0228	50.1	50.05
Requirement2	1100	10	50.1235	50.0472	50.2	50.1
Requirement3	576	2	50.4000	50.1950	50.5	50.2
Requirement4	508	5	50.4600	50.2200	50.7	50.3
Not tripping	-	-	50.8000	50.3800	-	-

It can be known from the table that the generator tripping solution solved by using the generator tripping optimization setting model meets the set requirements regardless of the highest frequency and steady-state frequency, and has certain conservativeness. At the same time, the frequency safety constraint expression is used as a constraint condition, and the generator tripping optimization model with the generator tripping quantity as the objective function can avoid excessive generator tripping.

5. Conclusion

This paper proposes a dynamic frequency safety constraint for power systems based on the power balance in the frequency dynamic process. For a given power disturbance and maximum frequency deviation requirements, if the system operating conditions meet this condition, the maximum frequency deviation of the system after the corresponding disturbance will be less than the required maximum frequency deviation. Compared with the traditional method of calculating the maximum frequency deviation value, this constraint condition is more concise and practical. At the same time, it fully considers the impact of the unit output limit in the system frequency modulation, and has a certain degree of conservativeness, which can ensure system security and facilitate better application and power system.

At the same time, based on the frequency safety constraint, a generator tripping optimization model for the high-frequency second line of defense is proposed in this paper. The generator tripping solution obtained by solving the model can make the system meet the highest frequency and steady-state frequency after a corresponding accident. The requirements are set and are conservative. At the same time, by incorporating the expression of frequency safety constraints into the constraint conditions, the optimization model with the minimum amount of tripping generators as the objective function enables the system to trip the minimum number of units while meeting the frequency safety constraints, avoiding excessive generator tripping.

6. Appendices

1. Derivation of the maximum scale factor δ :

Scale factor $\delta = \frac{\Delta f_{\max}}{t_m} / \frac{\Delta P_{OL0}}{T_s}$. The frequency dynamic curve of the system can be obtained as:

$$\Delta f = -\frac{\Delta P_{OL0}}{k_s} [1 - A_m e^{-\alpha t} \cos(\Omega t + \varphi)]$$

Where

$$\alpha = \frac{1}{2} \left(\frac{1}{T_G} + \frac{1}{T_f} \right), \Omega = \sqrt{\frac{k_s}{T_s T_G} - \alpha^2}, A_m = \frac{1}{2\Omega T_s} \sqrt{k_s k_G}, \varphi = \arctan \left(\frac{1}{\Omega} \left(\frac{k_s}{T_s} - \alpha \right) \right)$$

then the proportionality coefficient:

$$\delta = g(T_s, T_G, k_D, k_G)$$

δ is a function of four parameters T_s, T_G, k_D, k_G , the expression is more complicated. Use particle swarm algorithm to solve the maximum value. The result was 0.63511. The objective function convergence graph is shown in figure 1. A step test is performed on the transfer function consisting of the decision variables (that are the four parameters) corresponding to the optimal solution, and the results are shown in figure 2.

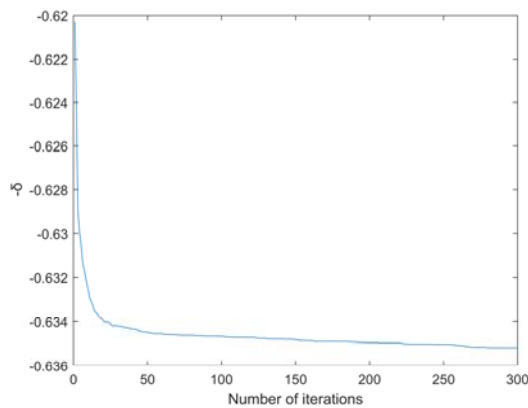


Figure A1. Convergence graph of objective function with number of iterations

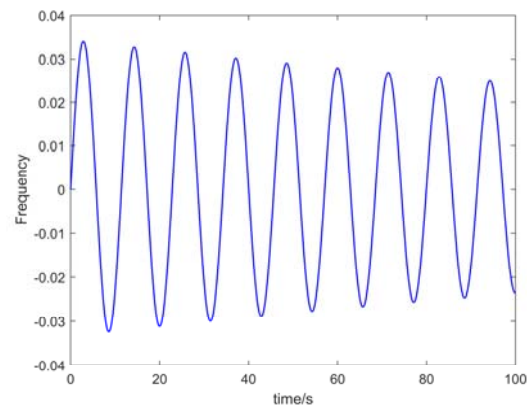


Figure A2. Step response of the system with optimal values of decision variables

Table A1. Optimal values of decision variables

Parameters	T_s	T_G	k_D	k_G
Results	50.3723	147.169	0	2391.93

It can be seen that the value of the decision variable tends to transform the expression into a sine curve without attenuation coefficient (observable from the value of the decision variable). The slope ratio of the initial derivative value of the sine function to the origin and the lowest point is $2/\pi$ (0.6366), which is similar to the particle swarm solution result (relative error 0.237%). That is, the δ limit is $2/\pi$.

The effect of the selection of δ on $\Delta P_m(t)$:

Substituting equation (3) and k into equation (4), we get:

$$\Delta P_m(t) = k_G \left(\Delta f_{\max} + \frac{T_g \Delta P \delta}{T_s} \left(e^{\frac{T_s \Delta f_{\max}}{T_g \Delta P \delta}} - 1 \right) \right). \text{ Let } \frac{T_s f_{\min}}{T_g \Delta P} = k', \text{ then } \Delta P_m(t) = k_G \left(\Delta f_{\max} + \frac{T_g \Delta P \delta}{T_s} \left(e^{\frac{k'}{\delta}} - 1 \right) \right), \text{ it is a}$$

function related only to δ ; for function $\delta \left(e^{\frac{k}{\delta}} - 1 \right)$ it can be found to decrease monotonically to δ .

Therefore, $\Delta P_m(t)$ has a minimum value when δ takes the maximum value. That is, $\Delta P_m(t)$ is conservative when δ takes its maximum value.

Table A2. Unit parameters

parameters	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6	Unit 7	Unit 8	Unit 9	Unit 10
P_i/MW	250	576	650	632	508	650	560	540	830	1000
P_{imin}/MW	150	200	300	300	250	300	250	250	400	500
T_s/s	84	60.6	71.6	57.2	52	52.8	69.6	48.6	69	1000
$K_G/(MW/Hz)$	16.37	81.86	120.31	120.31	81.86	120.31	81.86	81.86	160.42	225.56
T_G/s	2.94	3.62	3.72	3.62	3.72	3.62	3.62	3.72	3.62	2.94

Acknowledgments

This project was supported by National Natural Science Foundation of China (51922061), and Northeast Branch of State Grid Corporation of China.

References

- [1] National Economic and Trade Commission of the People's Republic of China. DL 755-2001. Safety and Stability Guidelines for Power Systems. Beijing: China Electric Power Press, 2001.
- [2] Zhang, Z. Xu, Y. Yuan, R.(2015)Frequency characteristics and high-frequency cut-off schemes of the sending-end power grid after the power grid is decommissioned in a large interconnected area. Power System Technology, 39 (1): 288-293.
- [3] Guo, Y.(2018) Research on optimization of high-frequency cut-off schemes in high-permeability wind power grids. Xi'an University of Technology.
- [4] Yue, H. Shao, G. Sun, M.(2019)High-frequency third-line defense line configuration method for large-scale new energy centralized delivery networks. Power System Technology, 43 (5)..
- [5] Zhang, Z. Yuan, R. Xu, Y.(2016) Optimization of high-frequency switching of the Sichuan power grid adapted to multi-circuit UHVDC [J]. Automation of Electric Power Systems, v.40; No.576 (02): 147-152..
- [6] Ye, J. Chen, Y. Chen L.(2015)Dynamic frequency optimization of single-pole blocking in Yunnan-Guangzhou DC island system. China Southern Power Grid Technology (2): 62-67. .
- [7] Zeng, J. Ye, X. Qu, X.(2018)Frequency Stability Characteristics and Control Strategy of Sichuan-Chongqing Transmission Network under the Asynchronous Interconnection Pattern. Electric Power Construction, 2018, 039 (001): 68-75. .
- [8] Shao, G. Hou, K. Wang, K.(2018)System protection scheme of over-frequency on the transmitting side of the UHVDC blocking system. Automation of Electric Power Systems, 42 (22): 35-40.
- [9] Gao, L. Dai, Y. Ma, Q. Zhang, L.(2009)Study on Primary Frequency Regulation Stability of Regional Interconnected Power Grid after UHV Line Decommissioning.Power System Technology, 33 (20): 27-32. .
- [10] Liu, K. Wang, X.(2014)Simulation study on the influence of power plant boilers and auxiliary equipment on the dynamic frequency of power system.Power System Protection and Control,42 (13): 53-58. 6.
- [11] Liu, L. Li, W. Chang, Y. Hu, X. Wang, M.(2019) Low-order simulation model of frequency lowest point estimation under high power loss.Automation of Electric Power Systems,43 (17): 78-86. 1.

- [12] Zhang, Y. Wen, D. Wang, X. Lin, J.(2019) Prediction of Frequency Curve after Power System Disturbance Based on Deep Confidence Network. Proceedings of the CSEE, 39 (17): 5095-5104 + 5290.
- [13] Alizadeh, M.Amraee, T.(2014) Adaptive scheme for local prediction of post-contingency power system frequency. Electric Power Systems Research, 107(2): 240–249.
- [14] Ahmadi, H.Ghasemi, H.(2014) Security-Constrained Unit Commitment With Linearized System Frequency Limit Constraints. IEEE Transactions on Power Systems, 29(4): 1536-1545.
- [15] Egido, I. Fernandez-Bernal, F. Centeno, P.(2009) Maximum Frequency Deviation Calculation in Small Isolated Power Systems. IEEE Transactions on Power Systems, 24(4):1731-1738.
- [16] Nhung, N. and Yosuke, N. (2018) Frequency Constrained Unit Commitment Considering Battery Storage System and Forecast Error, 2018 IEEE Innovative Smart Grid Technologies - Asia (ISGT Asia), Singapore, pp. 1171-1176.
- [17] Zhao, L.Zeng, B.(2012) Robust unit commitment problem with demand response and wind energy. 2012 IEEE power and energy society general meeting. IEEE, 2012: 1-8.
- [18] Zhao, J. Xu, C. Lu, X. Xu, C.(2017) Optimized allocation method of primary frequency regulation reserve capacity and energy storage of microgrid. Proceedings of the CSEE, 37 (15): 4324-4332 + 4572.
- [19] Min, Y. Chen, L. Jiang, Q.(2016) Power System Stability Analysis. Tsinghua University Press, Beijing.
- [20] Padberg, M.(2000) Approximating separable nonlinear functions via mixed zero-oneprograms.Operations Research Letters,27(1): 1-5.
- [21] Wang, C.Wei, W.Wang, J.(2017) Robust Defense Strategy for Gas-Electric Systems Against Malicious At-tacks. IEEE Transactions on Power Systems,32(4): 2953-2965.
- [22] Kundur, P.(1994)Power System Stability and Control.McGraw-Hill, New York.