IOP Conference Series: Earth and Environmental Science

PAPER • OPEN ACCESS

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To cite this article: Xuelian Wu *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **223** 012037

Study on the Improved Evaluation Method of Primary Frequency Modulation for Grid-connected Units

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Abstract. The primary frequency modulation function of generating units is an important means to maintain the frequency stability of the power grid. The reasonable assessment criteria help to regulate the primary frequency modulation performance of generating units and enhance the enthusiasm of units to participate in frequency modulation auxiliary services. On the basis of mastering primary frequency modulation principle, the response characteristics of the electro-hydraulic governor and the turbine under frequency excursion are analysed in detail. Aiming at the shortcoming of the current primary frequency modulation evaluation standard, an integral electricity algorithm with different weights added according to the contribution of primary frequency modulation is proposed. Finally, based on the concrete example, the correctness and rationality of the improved method are verified.

1. Introduction

Frequency is one of the important indicators to measure the electricity quality of the power grid. The primary frequency modulation function of the unit is an important means to maintain the frequency stability of the power grid. When the frequency of the power grid deviates from the rated value, the unit with primary frequency modulation function will utilize the regenerative heat in the boiler to adjust the output automatically according to the frequency variation of the system to improve the frequency stability of the system [1, 2].

In order to conduct a reasonable and effective assessment of the primary frequency modulation performance of the grid-connected units to evaluate the contribution to the grid, the power grid company of China has stepped up the management of the primary frequency modulation function of the grid-connected generators and has gradually carried out primary frequency modulation performance monitoring and assessment work in recent years [3, 4]. However, "Conditions and evaluation of grid-connected generator" clearly stipulates that the assessment indexes (such as the time lag of adjustment, the dead zone, the modulation coefficient, and the maximum adjusting range) are obtained by referring to design data, test reports or on-site inspections rather than actual operation of the units in actual accidents. Therefore, it can only check whether the setting of the unit's parameters meets the technical specifications and does not reflect the actual response of the unit accurately during the primary frequency modulation [5-7]. As the theoretical electricity is too ideal and it is much larger than the actual adjusting electricity, the rationality of assessment standards needs to be further studied [8].

In this paper, the response characteristics of the electro-hydraulic governor and steam turbine are analysed in detail under frequency excursion. An integral electricity algorithm with different weights according to the contribution to the system is proposed. The new assessment method will help to increase the enthusiasm of the grid-connected generating units to participate in the primary frequency modulation auxiliary service and regulate the primary frequency modulation performance of the generating units.

2. Primary frequency modulation function

2.1. The principle of primary frequency modulation

The primary frequency modulation function of the generator refers to the ability of the generating units to increase or decrease the output power automatically according to the frequency static characteristics of the speed governor and the frequency change of the system [9].The modulation coefficient reflects the unit's primary frequency modulation capability and is the most important indicator of the governor system. Assuming that the system frequency is rated frequency, the output of the unit is rated power; when the system frequency drops to, the output of the unit will increase to accordingly. The modulation coefficient of governor system is

$$\delta = \frac{\Delta f}{f_B} \cdot \frac{P_{FB}}{\Delta P} = \frac{\Delta f\%}{\Delta P\%} \tag{1}$$

Taking the economy and stability of the unit operation into account, in order to avoid frequent movements of the units because of the frequent fluctuations of the frequency, the units with primary frequency modulation function must be set to a certain dead zone. Only if the frequency excursion is over the dead zone, the governor will act. In order to avoid the large regulation of the unit in a short time, which affecting the stability of the system, it needs to limit the rate of the adjusting. Taking a unit with a rated capacity of 360MW as an example, the unit's modulation coefficient is designed to be 4%, the dead zone is ± 2r / min and the magnitude of the load adjusting is limited to ± 6%.

2.2. The response characteristics of electro-hydraulic governor

The response characteristics of the opening value signal and the output power of turbine will be analysed as follows.

2.2.1 The opening value signal. Common electro-hydraulic governor consists of the electro-hydraulic adjustment mechanism and electro-hydraulic servo mechanism, and the typical structural model is shown in figure 1.

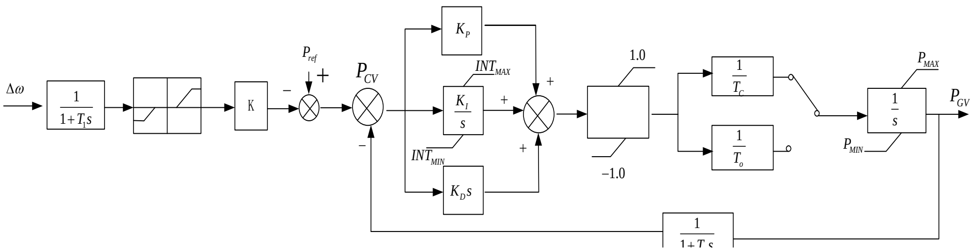

Figure 1. Structural model of electro-hydraulic control system

The transfer function of electro-hydraulic adjustment mechanism can be expressed as:

$$G_1 = \frac{P_{CV}}{-\Delta\omega} = \frac{K}{1+T_1 s} \tag{2}$$

Where: T_1 is the time constant of the speed measurement, the typical value is 0.02 seconds; K is the magnification of the speed excursion, and it is the reciprocal of the modulation coefficient.

Transfer function of the electro-hydraulic servo can be expressed as:

$$G2=\frac{P_{GV}}{P_{CV}}=\frac{\left(K_P+K_D s+\frac{K_I}{s}\right)\cdot\frac{1}{T_o}\cdot\frac{1}{s}}{1+\left(K_P+K_D s+\frac{K_I}{s}\right)\cdot\frac{1}{T_o}\cdot\frac{1}{s}\cdot\frac{1}{1+T_2 s}} \tag{3}$$

Where: T_2 is the feedback time of the servomotor, with the typical value of 0.02 seconds; T_o is the turning on time constant of the servomotor, with the typical value of 1-4 seconds; K_P, K_D and K_I are proportional magnification, differential multiple and integral multiple of the PID module, K_P and K_D are 0 generally, and K_I is about 10 under normal circumstances.

The transfer function can be reduced to a first-order delay function with the typical parameters, as shown in the following equation.

$$G2=\frac{P_{GV}}{P_{CV}}=\frac{1}{{T_0}/{K_P}\, s+1} \tag{4}$$

Where: the time constant ${T_0}/{K_P}$ is between 0.1 seconds to 0.4 seconds.

Under the power disturbance, when the frequency excursion does not reach the limiter of the governor, the opening signal of the governor will linear change with the frequency change. At this time, the amplitude of the variation of the unit's mechanical power is controlled by the governor's modulation coefficient, and when the frequency excursion reaches the limiter of the governor, the opening command will be a fixed value, which does not change with the frequency. The typical response curve of the system frequency and the governor's opening signal are shown in figure 2.

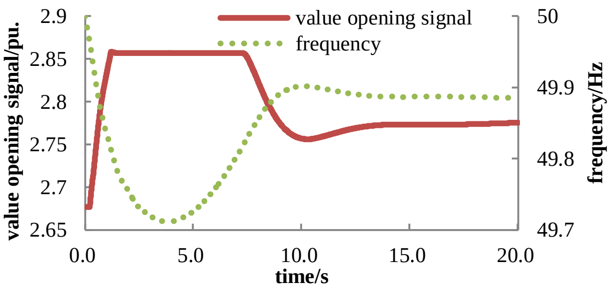

Figure 2. The governor's value opening signal and frequency response under power disturbance

2.2.2 Response characteristics of the turbine. When the governor's value opening command starts to change, the steam turbine will start to increase or decrease the intake air volume. Due to the release of heat storage of steam turbine requires a process, the change of actual mechanical power have a time delay effect. The structure of the turbine is shown in figure 3.

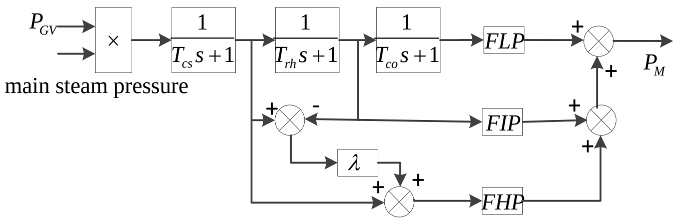

Figure 3. Transfer function model of the turbine

When the main steam pressure remains unchanged, the transfer function of the turbine can be obtained as

$$G_3=\frac{P_M}{P_{GV}}=\frac{1}{T_{cs}s+1}\frac{1}{T_{rh}s+1}\frac{1}{T_{co}s+1}FLP+\frac{1}{T_{cs}s+1}\frac{1}{T_{rh}s+1}FIP+\left[\frac{1}{T_{cs}s+1}+\lambda\left(\frac{1}{T_{cs}s+1}-\frac{1}{T_{cs}s+1}\frac{1}{T_{rh}s+1}\right)\right]FHP \tag{5}$$

Where, the typical time constant of steam volume T_{RH} is about 0.1 to 0.4 seconds; the time constant of reheater T_{RH} is about 4 to 11 seconds; the time constant of cross-tube is about 0.3 to 0.5 seconds. It can be seen that the delay of output power of the turbine is mainly determined by the time constant of reheater.

Under the active power disturbance, with the increase of the value opening signal, the opening of the valve gradually increases, and the output of the generating unit increases slowly; when the opening of the valve reaches the maximum, the actual output of the generating unit can't reach the maximum amplitude due to the inherent delay of releasing the heat by the steam turbine. With the gradual recovery of the frequency, the opening signal begins to decrease. With the decrease of valve opening, the output begins to return without reaching the theoretical maximum.

3. Improved evaluation standards

From the point of view of grid operation, the evaluation criteria of primary frequency modulation performance should be based on the actual contribution of the unit to the grid frequency, that is, assessing the integral electricity of primary frequency modulation during the high-frequency or low-frequency period of the grid, and it is a combination of a number of indicators of primary frequency modulation [10].

3.1. Conventional evaluation method

When the frequency exceeds the frequency modulation dead zone and the duration exceeds a certain time T, the contribution of the primary frequency modulation can be expressed as the integral electricity of the variation of the output power under the primary frequency control accounts for the proportion of the theoretical integral electricity in the period of the system frequency exceeding the dead zone (maximum value is 60 seconds).Namely

$$DX = \frac{\Delta Q_{sY}}{\Delta Q_{jY}} \times 100\% = \frac{\int_{t_0}^{t_0+t_e} (P_{St} - P_{ST})dt}{3600} / \frac{\int_{t_0}^{t_0+t_e} \Delta f(t) \times P_N / f_N / \delta dt}{3600} \times 100\% \tag{6}$$

t_0 is the time (in seconds) when the frequency reaches the boundary of the dead zone; t_e is the time (in seconds) when the system frequency exceeds the dead zone, (the maximum value is 60 seconds; if the frequency returns to within the dead zone within 60 seconds, the maximum time will be the moment when the frequency return to the dead zone); P_{ST} is the average value of the actual output of the unit within the first 30 seconds before the moment t_0; P_{St} is the actual output of the unit after the moment t_0; δ is modulation coefficient; dt is the interval time of integration, and it is 1 to 5 seconds usually; $\Delta f(t) = |f_t - f_N| - f_{sq}$, and f_t is the system frequency (in Hz) at time t; f_N is the rated frequency of the system; f_{sq} is the primary frequency modulation dead zone of the unit; P_N is the rated power of the unit.

3.2. Improved evaluation method

In order to make up for the deficiencies of the conventional assessment methods and fully consider the important contribution to the system in the time of frequency dropping, an integral electricity algorithm with additional weights is proposed.

At the initial stage of fault, the acceleration of frequency change is largest. The acceleration of frequency change gradually decreases with the decrease of unbalanced power of the system, and then the frequency gradually shifts to the extreme value following the disturbance. With the frequency modulation of the system, the frequency begins to recover gradually. The faster the primary frequency modulation response of the unit is, and the larger the modulation range is, the safer the system frequency will be. The contribution of the output power of the units is greater at the time of a faster rate of frequency change and a greater frequency excursion. Therefore, the frequency excursion and the rate of frequency change are considered as the index of the comprehensive coefficient. When the contribution coefficient of the frequency response is greater than a certain value, the product of the actual output of the unit and the coefficient is taken as the contribution of the unit and the ratio of the integral electricity of the actual output and the theoretical integral electricity is used as the evaluation standard. Specific methods are as follows:

First of all, the data should be normalized to make the original data standardized suitable for comparative evaluation of the indicators with same order of magnitude. A typical normalization method is min-max normalization, which is a linear transformation method, and the purpose is to make the result value is mapped between [0-1]. The conversion function is as follows.

$$x^* = \frac{x - \min}{\max - \min} \tag{7}$$

Where: max is the maximum value of the sample data; min is the minimum value of the sample data; x is the original value of the data; x^* is the processed value of the data.

Add the normalization result of frequency excursion and rate of frequency change, the comprehensive contribution coefficient is

$$k(t) = f^*(t) + f'^*(t) \tag{8}$$

Where: $f^*(t)$ is the normalization result of frequency excursion at time t; $f'^*(t)$ is the normalized result of the rate of frequency change at time t.

Then, the index of primary frequency modulation is

$$DX_1 = \frac{\int_{t_0}^{t_0+t_e} \eta(P_{St} - P_{ST})dt}{\int_{t_0}^{t_0+t_e} \Delta P dt} \times 100\% \tag{9}$$

When $\Delta P \geq \Delta P_{\max}$, $\Delta P = \Delta P_{\max}$; when $\Delta P < \Delta P_{\max}$, $\Delta P = \Delta f(t) \times P_N / f_N / \delta$ .When $k(t) \geq 1$, $\eta = k$; when $k(t) < 1$, $\eta = 1$.

Where: $\Delta P_{\max}$ is the maximum regulation of the units, and it can be determined by the primary frequency modulation test.

4. The verification of the improved evaluation

Under the active power disturbance, the value opening command begins to decrease from the maximum opening degree after 7.26 seconds, and the system frequency returns to the dead zone after 25 seconds. The actual mechanical power and theoretical power of the two generators in the system are shown in figure 4. Generator 1 has a rated capacity of 300MW and generator 2 has a rated capacity of 360MW.

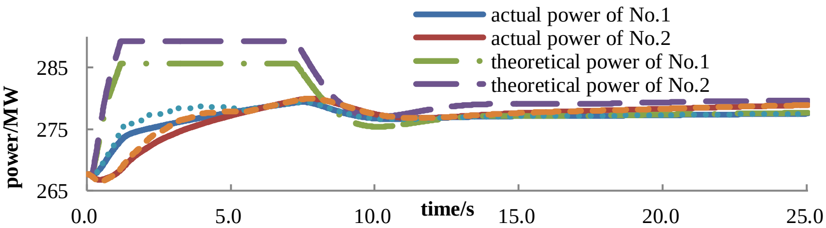

Figure 4. Mechanical power response curve of the generator under power disturbance

According to the algorithm proposed above, the curve considering the additional weights is shown by the dotted line in figure 4. The calculation results using the conventional evaluation method and the improved evaluation method are shown in the following table 1.

Table 1. The calculation results of different integral electricity algorithms

	Theoretical electricity /MW.s	Actual electricity /MW.s	Electricity with additional weights/MW.s	DX	DX1
Generator 1	291.44	229.48	236.86	0.79	0.81
Generator 2	349.73	231.49	236.31	0.66	0.68

In fact, within 25 seconds following the power disturbance, generator 1 contributes more integral electricity than generator 2 due to the more output in the late stage of frequency recovery. However, as can be seen from figure 4, during the first 5 seconds when the system frequency drops rapidly, generator 1 generates more power and suppresses the drop of system frequency more effectively. Integral electricity of generator 1 is slightly larger than generator 2 when the additional weights are considered. Due to the larger capacity of generator 2, the theoretical integral electricity of generator 2 is larger, and the performance index is obviously inferior to that of generator 1.

5. Summary

The evaluation of the primary frequency modulation performance of the units plays an important role in regulating and encouraging the unit to give full play to the primary frequency modulation capability and maintain the frequency stability of the system. An integral electricity algorithm with different weights according to the contribution to the system is proposed. By adding a certain amount of compensation electricity on the basis of the actual output of the unit, the unit is encouraged to adjust the output more quickly and faster to restrain the rapid change of frequency and support the recovery of system frequency. Through the verification of example, it can be seen that compared with the conventional integral electricity algorithm, the improved method can characterize the primary frequency modulation performance more accurately.

Acknowledgements

This work was supported by Electric Power Research Institute of State Grid Chongqing Electric Power Company (The Science and Technology Project of “Research on Primary Frequency Modulation Performance Simulation and Evaluation Method for Chongqing Main Thermal Power Units”).

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