Simulation Analysis of Frequency Regulation

Zhijian Liu1,a, Xiaoya Chen1,*, Linglin Luo1,b, Yanhong Wang1,c, Xiaoxin Liu2,d and Sha Yu1,e

1School of Electric Power Engineering, Kunming University of Science and Technology, Kunming, China
2Nujiang Power Supply Bureau of Yunnan Power Grid Co., Ltd., Nujiang, China

*Corresponding author e-mail: fcplxy666@163.com, a248400248@qq.com, b65016642@qq.com, c574044984@qq.com, d1149410854@qq.com, e2500418169@qq.com

Abstract. Frequency is one of the most important parameters reflecting the operation quality of the system. When the system is in steady-state operation, the frequency of the generator in the system is equal under steady-state operation. Because the load is changing at any time, this kind of balance is dynamic. The only way to maintain dynamic balance is to adjust the input power of the generator, so that the actual output of the generator can closely track the change of the load and keep the balance between supply and demand of active power. The essence of frequency control is to regulate and control the active power of all generators in power grid. In this paper, the principle of frequency fluctuation is analyzed, and the physical models of the primary and secondary frequency modulation are established. The simulation results verify the differential regulation of the primary frequency modulation and the no-difference regulation of secondary frequency modulation. It provides an effective basis for the later research of AGC control strategy.

1. Introduction

The operating point of power system is constantly changing under the influence of environment and climate. The fixed gain controller of the traditional control algorithm cannot satisfy the standard with non-linear and strong randomness to achieve frequency control. The balance state of load demand and power generation can be reflected by the frequency of the AC power system. Maintaining the stability of the power system frequency is also the most basic responsibility of power dispatching.

Automatic generation control is to keep the frequency stability by tracking the load changes in the system through the control of generator output [1]. The traditional regional power grid is divided into different territorial parts. Considering the consistency synergy theory, the adjustment cost and climbing time are taken as objective functions, and a power dynamic allocation model is proposed, which effectively solves the problem of decentralized autonomy [2]. Reference [3] considers three-area interconnected power grids, and focuses on the analysis of the influence of relevant parameters on the stability of primary frequency modulation system. Especially, some important parameters such as equivalent speed regulation inequality, control system delay and grid rotational inertia time are studied. Reference [4] by discussing the limitation of frequency modulation of hydropower units, the adjustment range of hydropower units is suggested in view of the reasons for the elevation of
hydropower units in primary frequency modulation, and the reasons for the combination of primary
frequency modulation and AGC are analyzed. Reference [5], a reasonable allocation method of
regional frequency modulation responsibility is proposed, which takes the quality of frequency and the
fair allocation of regional frequency modulation responsibility as the optimization objective, combined
with the setting of frequency deviation coefficient. Finally, the ideal secondary frequency modulation
characteristics can be achieved from top to bottom. Reference [6] by setting up a measuring platform
of power grid frequency, the general distribution characteristics of power grid frequency are obtained
by analyzing the measured data. The main reason for the distribution is the influence of load
fluctuation bandwidth and the non-linearity of AGC control strategy. Reference [7] analyzed the main
technical problems faced by the traditional power grid after the completion of the power market.
Based on the background of the power market, the specific steps to realize the AGC ancillary service
market were put forward.

Reference [8] focuses on the problem of secondary frequency modulation, and proposes an AGC
control model based on electromechanical transient through the modeling method of hybrid systems.
Reference [9] regards batteries as representative of new energy storage resources, which can rapidly
change the output distribution of power. The capacity requirement of secondary frequency modulation
for energy storage is analyzed emphatically, and the frequency analysis method of discrete Fourier
transform is proposed. Reference[10] according to the actual situation of Henan power grid, the AGC
frequency modulation control of hydrothermal power coordinated control is established, and the actual
simulation experiment is carried out, and the reasonable control scheme is put forward. Reference [11]
puts forward that the evaluation method of primary frequency modulation cannot accurately reflect the
effect of primary frequency modulation, and evaluates the effect of primary frequency modulation
according to several groups of output characteristic curves. Reference [12] introduces multi-agent
equalization algorithm to solve the problems caused by the random nature of new energy access to
interconnected power grids, and uses the equilibrium probability selection mechanism to search.
Reference [13] applies reinforcement learning of Markov chain decision theory to the control process
of AGC. The simulation results show that the control process of AGC is non-linear. Reference [14]
combines genetic algorithm with deep learning algorithm in the AGC control strategy. The simulation
results in three regions show that the method is good in the non-linear control.

Frequency changes at different times will have an impact on the operating equipment and safety.
Based on the principle of primary frequency modulation, this literature establishes a two-area
interconnected primary frequency modulation model. The simulation results show that the system
passes through a transient process, and the frequency of the two-area system is stabilized to 49.94 Hz
after a short period of oscillation by primary frequency modulation, with a frequency deviation of 0.06
Hz, which is within the allowable range. The parameters of the secondary frequency modulation
simulation model are consistent with those of the two-area interconnected primary frequency
modulation model. Combining the primary frequency modulation with the secondary frequency
modulation in the actual power grid system, the simulation verifies that under the tie-line frequency
control mode, by comparing the waveforms, it is obvious that the frequency of the system is stabilized
at 50 Hz through the secondary frequency modulation, and achieves no error regulation. The
simulation results verify that the differential regulation of primary frequency modulation and the no-
difference regulation of secondary frequency modulation provide an effective basis for the later
research of AGC control strategy.

2. Cause analysis of frequency fluctuation in power grid

The power system is in stable operation state, and the speed n and frequency f of each generator in the
system satisfy the equation:

\[ f = \frac{pn}{60} = \frac{w}{2\pi} \]  (1)
In the formula, $w$ is the angular speed of synchronous generator, $p$ is the logarithm of generator poles, the steam turbine is usually one pair, and the hydroelectric generator is usually $20 \sim 40$ pairs.

The frequency of power grid composed of several synchronous generators in parallel is closely related to the rotor motion. The rotor motion equation of synchronous generators is as follows:

$$
\begin{align*}
T_m - T_e &= \frac{Jdw}{dt} = \Delta T \\
P_m - P_e &= 2H_s \Delta w
\end{align*}
$$

In the formula, $\Delta \omega$ is the variation of angular velocity; $H_s$ is the inertia constant of generator; $J$ is the inertia of generator; $P_m$ is the mechanical power of prime mover; $P_e$ is the electromagnetic power of generator; $T_m$ and $T_e$ are the input mechanical torque and output electromagnetic torque, respectively.

When there is power shortage in the network, $T_m - T_e < 0$, the kinetic energy of the rotor will be decreased and $dw/dt < 0$, and the consumption of the kinetic energy of the rotor will make the rotational speed of the unit drop. If the system does not take any measures and there is no frequency modulation device, the system frequency will continue to decline. Then in the actual power system, the unit is usually equipped with a governor, which can prevent the system frequency from unrestricted reduction through primary frequency modulation. If the mechanical power and electromagnetic power of the prime mover do not match, it will inevitably lead to the change of $\Delta \omega$, the frequency fluctuation, and the stability of the system will be destroyed. In the actual power grid operation, the mechanical power of the prime mover is constantly changing, and its value is related to the characteristics of the governor, which is relatively easy to control, while the change of the electromagnetic power of the generator is related to its own electromagnetic characteristics and system load characteristics, which is difficult to control. Therefore, the main reason for the frequency fluctuation of power grid is the change of electromagnetic power which is not easy to control.

In order to maintain the constant speed of each generator in the network, it is necessary to balance the output power of the generator with the input power of the prime mover. Because the power load is changing at any time, this kind of balance is dynamic. The only way to maintain dynamic balance is to adjust the input power of the generator at any time, that is, to continuously adjust the intake water or air of the generator, so that the actual output of the generator can closely track the change of the load and maintain the balance between supply and demand of active power. Therefore, the essence of frequency control is to regulate and control the active power of all generators in power grid. The regulation and control of the active power output of the system is a passive tracking regulation process. The opening of the guide vane or the regulation of the valve has mechanical inertia, which cannot catch up with the instantaneous change of the power load. Therefore, it is impossible to keep the frequency unchanged absolutely, and it can only be stabilized in a small allowable range.

3. Simulation and analysis of the frequency modulation study

3.1. Frequency Modulation Example 1
It assumes that the generators in the same area have the same characteristics as the coherent group. All generators in the same region are equivalent to a generator with equivalent moment of inertia and equivalent damping coefficient. Therefore, all generators in the same area can be equivalent to a generator. Combined with the above analysis, the primary frequency modulation simulation model of the interconnected two-machine and two-area is built with the equivalent first-order transfer function of the governor, the prime mover and the system as shown in Figure 1.
Figure 1. Primary Frequency Modulation Model of Two-area interconnected power grid

The simulation sets that the input of the two regions is 0, the load disturbance of 0.02pu is applied in region A, and the load disturbance of 0.03pu is added to region B. The parameters of the regional model are taken from reference [15]. In order to be convenient to analysis, the corresponding parameters of the two regions are identical. The waveforms obtained by MATLAB/SIMULINK simulation are as follows:

Figure 2. Frequency response curve
The simulation time is set to be 50 seconds, and the step load disturbance of 0.02pu is added in area A and 0.03pu is added in area B at the beginning of the simulation. After a transient process, the frequency of the two-area system is stabilized at 49.94Hz after a short period of oscillation by the primary frequency modulation, with a frequency deviation of -0.06Hz, which is within the allowable range. Looking at Figure 3, the tie-line switching power reaches a stable value of 0.005pu at about 13s. Only under the primary frequency modulation, the system can restore stability, but the system frequency can not return to be 50Hz. The primary frequency modulation is a differential regulation. In order to achieve no difference regulation, the primary frequency modulation needs to cooperate with secondary frequency modulation to make the system without frequency deviation, and the tie-line power deviation is 0, and to achieve better control effect.

3.2. Frequency Modulation Example 2
When the system is disturbed or malfunction occurs, the primary frequency modulation can not make the actual frequency of the system return to the rated frequency, only through the addition of secondary frequency modulation to achieve frequency control [16]. Although the response speed of secondary frequency modulation is not as fast as that of primary frequency modulation, it also plays an important role in system frequency control and is an important means of frequency control. Literature [17] focuses on the problem of secondary frequency modulation, and proposes an AGC control model based on electromechanical transient through the modeling method of hybrid systems. In reference [18], a reasonable allocation method of regional FM responsibility is proposed, which takes the quality of frequency and the fair allocation of regional FM responsibility as the optimization objective, combined with the setting of frequency deviation coefficient. Finally, the ideal secondary frequency modulation characteristics can be achieved from top to bottom.

The simulation model of two-area secondary frequency modulation is built by MATLAB/SIMULINK software as shown in Figure4. The simulation parameters are consistent with those of the primary frequency modulation model of two-area interconnected power grid.
Figure 4. Secondary Frequency Modulation Model for Two-Area Interconnected Power Grid

It is similar to the two-area interconnected power grid primary frequency regulation simulation example, the load disturbance of 0.02pu is applied in area A and 0.03pu is applied in area B. The simulation results show that the waveform is as follows:

![Figure 5. Frequency response curve](image-url)

![Figure 6. Power increment of unit regulation](image-url)
The simulation model adopts the tie-line power and frequency deviation control mode. The simulation time is set to 50 seconds, and the system is adjusted by about 20 seconds. After secondary frequency modulation, the frequencies of both regions recovered to 50Hz without frequency deviation. Observed in Figure7, when the simulation time is about 36 seconds, the power deviation of tie-line is restored to 0, and the planned tie-line switching power is the same as the actual tie-line switching power. As shown in Figure8, the ACE values of the two regions are also stable at 0.

From the power curve of unit regulation, it can be seen that the load variation in area A is 0.02pu and in area B is 0.03pu. It is verified that when the set frequency deviation coefficient is the same as the natural frequency characteristic coefficient, the absolute value of regulating power PG in the area with load variation is equal to the load variation, and the area with load variation participates in the AGC unit only, while the area without load variation PG is 0, and no AGC adjustment is carried out. Through the above analysis and waveform comparison, it is obvious that the system frequency, tie-line power and regional control deviation can be restored to the original equilibrium state after secondary frequency modulation, and achieve no error adjustment.

4. Conclusion
(1) Firstly, the research status of FM control strategy is summarized and analyzed, and its shortcomings are pointed out. Frequency in power system is one of the important parameters reflecting the operation quality of the system. The change of frequency at different times will affect the operation equipment and safety.

(2) The principle of frequency fluctuation in power grid is analyzed and the relationship between frequency and speed is discussed from the mathematical model. The physical model of power system in stable operation state can draw a conclusion that the essence of frequency control is the regulation and control of active power of all generators in power grid.

(3) The primary frequency modulation stabilizes the frequency of the two-area system to 49.94 Hz after a short period of oscillation, with a frequency deviation of 0.06 Hz, which is within the allowable range. The parameters of the secondary frequency modulation simulation model are consistent with those of the two-area interconnected primary frequency modulation model. Combining the primary frequency modulation with the secondary frequency modulation in the actual power grid system, the simulation verifies that under the tie-line frequency control mode, by comparing the waveforms, it is obvious that the frequency of the system is stabilized at 50 Hz through the secondary frequency modulation, and achieves no error regulation.

References
[1] Hu Binqi. Research of Control Strategy for AGC Based on Control Performance Standard [D].
Huazhong University of Science and Technology, 2005.

[2] Zhang Xiaoshun, Yu Tao. Virtual Generation Tribe Based Collaborative Consensus Algorithm for Dynamic Generation Dispatch of AGC in Interconnected Power Grids [J]. Proceeding of the CSEE. 2015, 35 (15): 3750-3759.

[3] Gao Lin, Dai Yiping Ma Qingzhong, et al. Research on Stability of Primary Frequency Regulation of Interconnected Power System After Trip-Out of Ultra High Voltage Transmission line [J]. Power System Technology, 2009, 33 (20): 27-32.

[4] Xu Guangwen, Huang Qingsong, Yao Ze, et al. Discussion on Limiting of Primary Frequency in Hydropower Units and Coordination Norm for AGC [J]. GUANGDONG ELECTRIC POWER, 2011, 24 (04): 46-48+53.

[5] Liu Le, Liu Rao, Li Weidong. Area Frequency Regulation Obligation and Its Distribution Mode in Interconnected Power System [J]. Automation of Electric Power Systems, 2008 (16): 20-23+37.

[6] Cheng Hanmiao, Li Hongbin, Shao Zhouce, et al. Research on Distribution of Power Frequency considering on Multiple Influence Factors [J]. Power System Protection and Control, 2017, 45 (12): 9-15.

[7] Gui Xianming, Li Mingjie. Researches on How to Improve the Traditonal AGC Technology While Electricity Market is Established [J]. Automation of Electric Power Systems, 2000 (09): 48-51.

[8] Song Xili', Wang Chengshan', Zhong Wuzhi, et al. Modeling of Automatic Generation Control for Power Systems Transient, Medium-Term and Long-Term Stabilities Simulations [J]. Power System Technology, 2013, 37 (12): 3439-3444.

[9] Hu Zechun, Xie Xu, Zhang Fang, et al. Research on Automatic Generation Control Strategy Incorporating Energy Storage Resources [J]. Proceedings of the CSEE, 2014, 34 (29): 5080-5087.

[10] Sun Suqin, Teng Xianliang, Dai Fei. Experimental Investigation on Coordinate Control Between Hydro Units and Thermal Units in Henan Power Grid [J]. Automation of Electric Power Systems, 2008 (06): 99-103.

[11] Zhang Yanjun, Gao Kai, Qu Zuyi,.An Evaluation Method of Primary Frequency Modulation Performance Based on Characteristics of Unit Output Power Curves [J]. Automation of Electric Power Systems, 2012, 36 (07): 99-103.

[12] Wang Huazhi, Yu Tao, Tang Jie. Automatic Generation Control For Interconnected Power Grids Based on Multi-agent Correlated Equilibrium Learning System [J]. Proceedings of the CSEE, 2014, 34 (04): 620-627.

[13] Imthias TP, Nagendra PS, Sastry PS .A reinforcement learning approach to automatic generation control [J]. Electric Power Systems Research, 2002, 63 (1): 9-26.

[14] Daneshtfar GA-based F, Bevani H .Load-frequency control:a multi-agent reinforcement learning [J].Transmission IF Proceedings Distribution. of Generation and 2010, 4 (1): 13-26.

[15] C Elgerd-O-I-and-Fosha. Optimum megawatt-frequency control of multiarea electric energy system s[J]. IEEE Trans on Power Apparatus&Systems, 1970, vol.PAS-89 (4): 556-563.

[16] Zhao Wangzong, Li Bin, Wei Hua, et al. The Optimal AGC Control Stategy Considering the Primary Frequency Regulation under the Control Performance Standard for the Interconnected Power Grid [J]. Proceedings of the CSEE, 2016, 36 (10): 2656-2664.

[17] Feng Peilei, Li Yan, Xu Tianqi, et al. Research on Modeling of Impact Hydraulic Turbine Reflector [J]. YUNNAN ELECTRIC POWER, 2018, 46 (01): 11-15.

[18] Liu Le, Liu Rao. Li Weidong. Area Frequency Regulation Obligation and Its Distribution Mode In Interconnected Power System [J]. Automation of Electric Power Systems, 2008, 32 (16): 20-23, 37.