Unit Commitment Considering the Different Frequency supporting capability of Synchronous Generators

Jiaqi Zhang*, Guoyi Xu, Beibei Li, and Lei Han

State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources (North China Electric Power University), Beijing 102206, China

Abstract. With the high penetration of renewable power in the power system, the inertia level and frequency regulation capability are reduced, the system frequency safety are facing a major challenge. Considering the different frequency support capability of the synchronous generators, the effect of adjustment coefficient of different units on the minimum frequency has been analyzed based on the sensitivity analysis. A multi-objective frequency constraint unit commitment model considering the sensitivity of adjustment coefficient is proposed, and simulation results show that the proposed model increases the minimum frequency value, improves the frequency stability of the power system.

Keywords. unit commitment, frequency response, adjustment coefficient, frequency constraint

1 Introduction

With the high penetration of renewable power in the power system, the proportion of synchronous units decreases, resulting in the reduction of the system inertia level and frequency regulation capacity[1-3], the frequency security is facing major challenges[4].

The traditional unit commitment requires the turbines to reserve a certain proportion of active power to provide frequency regulation[5]. But when the disturbance increases, further increase of reserve capacity will reduce the economic benefits of system operation[6]. Therefore, it is necessary to optimize the unit commitment model to ensure the system frequency safety.

In order to solve the problem of frequency stability, many scholars add frequency constraint to the unit commitment model, considering the frequency regulation methods of wind power, solar power and other renewable power[7-9]. On the basis of average system frequency modle(ASF model), the reference[10] considers the virtual inertia control and primary frequency regulation of wind turbine, constructs the unit commitment model considering the minimum frequency constraint. The references[11-12] consider the dynamic constraints of the maximum rate of change of frequency (RoCoF), maximum frequency deviation and steady-state frequency deviation in the whole process. However, at present, most of renewable energy units still use maximum power point tracking to control their output, the frequency regulation capability is limited. Most of the frequency regulation requirements are still supported by synchronous generators. In addition, the proportion of synchronous generators will decline in the future, how to make full use of the limited synchronous generators resources to adjust the frequency fluctuations is of great significance. However, the existing literature on unit commitment lacks consideration of the difference in frequency regulation capability of synchronous units.

In this paper, a multi-objective frequency constraint unit commitment model considering the sensitivity of synchronous generator adjustment coefficient is proposed. The effect of adjustment coefficient of different units on the maximum frequency deviation has been analyzed based on the sensitivity analysis. Then, the sensitivity factor is added to the unit commitment model to adjust the starting sequence of the units, so as to maximize the frequency regulation ability of each synchronous generator and improve the system frequency response ability. NSGA-II is used to solve the model. Finally, a 10-machine 39-bus system with wind turbines is utilized to validate the proposed model.

2 Sensitivity analysis of adjustment coefficient

After the disturbance occurs, the characteristic quantities used to describe the frequency change include: RoCoF $d\Delta f/dt$, maximum frequency deviation Δf_{max} or minimum frequency f_{nadir}. Among them, the maximum frequency deviation Δf_{max} can reflect the ultimate limit state of the frequency response process[13].

Compared with inertia, dead zone and other parameters, the adjustment coefficient R has a greater impact on the maximum frequency deviation[14]. Therefore, the maximum frequency deviation of the system after disturbance is further analyzed from the angle of the adjustment coefficient.

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[*] Corresponding author: letizia1698@163.com

For a multi-machine system, due to the difference of disturbance location, unit inertia and frequency response characteristics, the contribution of different generators to system frequency regulation is different[15]. So in the unit commitment problem, when the load demand increases at the following moment, and a new unit is required to start up, the frequency deviation after disturbance will be different when selecting different units to start up. This difference is difficult to be clearly described. Therefore, the introduction of the concept of sensitivity of adjustment coefficient can effectively reflect the results of the comprehensive impact of various factors[16].

Through the simulation of the system, it is convenient to obtain the frequency change process of the system after different types of disturbances. First, obtain the maximum frequency deviation value, and then we can calculate the sensitivity of different generator nodes.

Suppose there are n generator nodes, and the sensitivity S_{Ri} of the *ith* generator can be expressed as:

$$S_{\mathrm{R}i}=\frac{\left|\Delta f_{\max}(R_0+\Delta R_i)-\Delta f_{\max}(R_0)\right|/\Delta f_{\max}(R_0)}{\Delta R_i/R_0} \quad (1)$$

Where: $S_{\mathrm{R}i}$ is the sensitivity of the adjustment coefficient of the *ith* generator, indicating the relative change of the maximum frequency deviation caused by the adjustment of the adjustment coefficient, which can reflect the ability of generator to support the system frequency; i=1,2,…,n; $\Delta f_{max}(R_0)$ is the maximum frequency deviation, ΔR_i is the perturbation of the adjustment coefficient of the *ith* generator, $\Delta f_{max}(R_0+\Delta R_i)$ is the maximum frequency deviation after the adjustment of the adjustment coefficient of the *ith* generator.

3 Unit commitment model considering sensitivity and frequency constraints

3.1. Objective function

Traditional unit commitment model usually aims at the lowest generation cost. On this basis, the sensitivity of the adjustment coefficient is taken as the second objective function to form a multi-objective problem:

$$\begin{cases}\min f_1=\sum_{i=1}^{n}\sum_{t=1}^{T}\left[\left(a_i+b_iP_{it}+c_iP_{it}^2\right)+u_{it}\left(1-u_{i,t-1}\right)B_i\right]\\ \min f_2=\sum_{i=1}^{n}\sum_{t=1}^{T}u_{it}\frac{1}{S_{Ri}}\end{cases} \quad (2)$$

Where: f_1 is the power generation cost; n is the total number of generators; T is the total scheduling period; P_{it} is the output of the *ith* generator at time t; a_i, b_i and c_i are the generation cost coefficients of the *ith* generator; u_{it} is the operation status of the *ith* generator at time t, 1 indicates startup and 0 indicates shutdown; B_i is the start-up cost of the *ith* generator; f_2 is the reciprocal of the sum of sensitivities, since it is desired to start the units with high sensitivity first.

3.2. Constraints of traditional unit commitment

The constraints of the traditional unit commitment problem are as follows.

(1)Power Balance Constraints:

$$\sum_{i=1}^{n}u_{it}P_{it}+P_{wt}=P_{\mathrm{L}t} \quad (3)$$

Where: P_{wt} is the output of wind turbine at time t; P_{Lt} is the total load demand at time t.

(2) Generation Limits:

$$P_{i,\min}\le P_{it}\le P_{i,\max} \quad (4)$$

Where: $P_{i,\min}$ and $P_{i,\max}$ are the lower and upper limits on generator active power of the *ith* generator.

(3) System Reserve Constraints:

$$\sum_{i=1}^{n}u_{it}(P_{i,\max}-P_{it})\ge\lambda P_{\mathrm{L}t} \quad (5)$$

Where: λ is the reserve factor, taken as 0.05.

(4) Ramp Limits:

$$-D_{i,\mathrm{down}}\le P_{it}-P_{i,t-1}\le D_{i,\mathrm{up}} \quad (6)$$

Where, $D_{i,\mathrm{down}}$ and $D_{i,\mathrm{up}}$ are the maximum limit values of the output drop and rise of the *ith* generator.

(5) Minimum Startup and Shutdown Time Limits:

$$X_{\mathrm{S}it}\ge T_{\mathrm{S}i}\ 、\ X_{\mathrm{O}it}\ge T_{\mathrm{O}i} \quad (7)$$

Where: $X_{\mathrm{S}it}$ and $X_{\mathrm{O}it}$ respectively represent the number of hours that the *ith* generator has been offline or online; $T_{\mathrm{S}i}$ and $T_{\mathrm{O}i}$ respectively represent the minimum hours that the *ith* generator should be offline or online.

3.3. Frequency Limit Constraints

The ASF model of multi-machine system is established as shown in Fig.1:

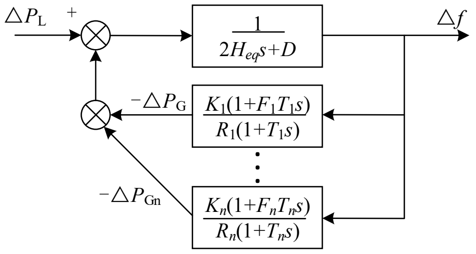

Fig. 1 ASF model

It can be seen from Fig.1:

$$\Delta P_{\mathrm{L}}-\sum_{i=1}^{n}\frac{K_i(1+F_iT_is)}{R_i(1+T_is)}\Delta f=(2H_{eq}s+D)\Delta f \quad (8)$$

Where, ΔP_{L} represents power disturbance; K_i is the mechanical power gain factor of the *ith* generator; F_i is the power factor from HP turbine of the *ith* generator; T_i is the governor time constant of the *ith* generator; R_i is the static adjustment coefficient of the *ith* generator; D is the load damping factor; H_{eq} represents the equivalent inertia of the system.

Replace all T_i in equation (8) with the unified Teq[10]:

$$\Delta f=\frac{\Delta P_{\mathrm{L}}(1+T_{eq}s)}{(2H_{eq}s+D)(1+T_{eq}s)+\sum_{i=1}^{n}\frac{K_i}{R_i}(1+FT_{eq}s)} \quad (9)$$

Get the frequency domain expression of frequency deviation, then the time domain expression of Δf can be obtained by inverse Laplace transform. Take the derivative of it, make $d\Delta f(t) / dt=0$, we can get the time t_m when the frequency reaches the lowest point, and the maximum frequency deviation(p.u.):

$$\Delta f_{\max} = -\frac{\Delta P_L}{D+R_{eq}}[1+e^{-\xi\omega_n t_m}\sqrt{\frac{1+T_{eq}{}^2\omega_n^2-2T_{eq}\xi\omega_n}{1-\xi^2}}\cos(\omega_n\sqrt{1-\xi^2}t_m-\theta)] \tag{10}$$

$$t_m = \frac{1}{\omega_n\sqrt{1-\xi^2}} tg^{-1}\frac{T_{eq}\omega_n\sqrt{1-\xi^2}}{T_{eq}\omega_n\xi-1} \tag{11}$$

$$\theta = tg^{-1}\frac{\xi - T_{eq}\omega_n}{\sqrt{1-\xi^2}} \tag{12}$$

Where: ω_n is the natural frequency; ξ is the damping ratio：

$$\begin{cases} \omega_n = \sqrt{\dfrac{D+R_{eq}}{2H_{eq}T_{eq}}} \text{、} \xi = \dfrac{2H_{eq}+(D+F_{eq})T_{eq}}{2\sqrt{2H_{eq}T_{eq}(D+R_{eq})}} \\ R_{eq} = \sum_{i=1}^{n}\dfrac{K_i}{R_i} \text{、} F_{eq} = \sum_{i=1}^{n}\dfrac{K_i}{R_i}F_i \end{cases} \tag{13}$$

The frequency constraints can be constructed as:

$$f_{c1} \ge f_N + f_N\Delta f_{\max} \ge f_{c2} \tag{14}$$

where, f_{c1} and f_{c2} are the upper and lower limits of frequency, which are generally set as the setting values of the system's high frequency machine cutting and low frequency load shedding.

3.4. Optimization steps considering sensitivity and frequency constraints

The steps of unit commitment considering the sensitivity of adjustment coefficient and frequency constraints proposed in this paper are as follows:

Step 1: Based on the system's grid structure, load forecast, etc, prepare the expected contingency set.

Step 2: Conduct offline simulation for the disturbances in the contingency set, calculate the sensitivity of each synchronous generator according to formula (1), get the sensitivity order, form the expected contingency sensitivity information set.

Step 3: Choose the accident with the most serious impact on the system, and search the corresponding sensitivity order information in the contingency set.

Step 4: Add the sensitivity information into the unit commitment as an objective function, establish a multi-objective unit commitment optimization model. Set the starting sequence of the synchronous units, give priority to the units with high sensitivity of the adjustment coefficient. NSGA-II is used to solve the problem.

4 Simulation calculation and analysis

Based on the IEEE 10-machine 39-bus system with wind turbines, the unit commitment model proposed in this paper is verified by using MATLAB and PSASP simulation software. The parameters of synchronous genetators are referred to [17], and the load data and wind power prediction data are referred to [18],, D=2.

4.1 Calculation of the sensitivity of adjustment coefficient

According to the calculation steps proposed in subsection 3.4, taking the sudden increase of load disturbance as an example, calculate the minimum frequency when different load node increased 150MW, and the results are shown in Table 1.

Table 1. Minimum frequency when different load increased 150MW

Load node	f_{nadir}/Hz	Load node	f_{nadir}/Hz	Load node	f_{nadir}/Hz
L3	49.6763	L18	49.6757	L27	49.6748
L4	49.6765	L20	49.6672	L28	49.6635
L7	49.6775	L21	49.6754	L29	49.658
L8	49.6771	L23	49.6751	L31	49.6588
L12	49.6825	L24	49.6754	L39	49.6590
L15	49.6762	L25	49.6641		
L16	49.6746	L26	49.6737		

According to the results in Table 1, select L29 as the disturbance node, which has the biggest frequency deviation under the same disturbance. Set load L29 increase 150MW, and calculate the sensitivity according to Equation (1). The results are shown in Table 2:

Table 2. Sensitivity of units when load29 increased 150MW

	S/%		S/%		S/%
G30	3.8012	G34	2.3392	G37	3.5088
G31	3.6550	G35	3.3626	G38	4.5322
G32	3.5088	G36	3.0702	G39	4.5322
G33	3.2164				

It can be obtained that under the L29 increase of 150 MW, the sequence of the sensitivity is:

G38,G39>G30>G31>G32,G37>G35>G33,G36>G34

4.2 Simulation analysis of unit commitment

Set the minimum frequency limit of the frequency constraint to 49Hz [19]. Set load L29 increase, and the power gap is 10% of the total load at that time. Compare the unit commitment results of these two cases:

Case 1: consider frequency constraints
Case 2: consider synchronous units' sensitivity sequence of adjustment coefficient and frequency constraints

4.2.1 Startup and shutdown status

NSGA-II algorithm is used to solve the model, and the startup and shutdown states of the two cases are shown in Figure 2 and Figure 3.

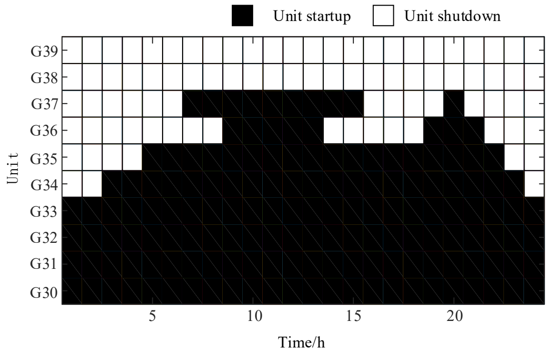

Fig. 2. Units' on-off conditions without considering sensitivity

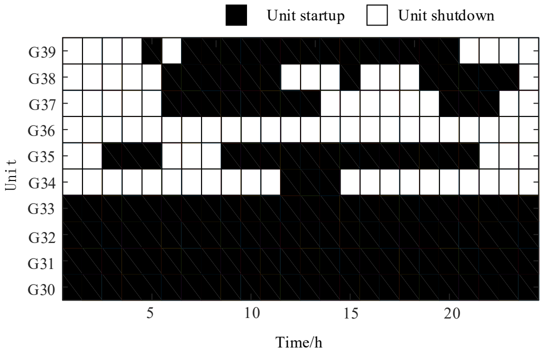

Fig. 3. Units' on-off conditions considering sensitivity

It can be seen from Figure 2 and Figure 3 that the total number of online units at each time under the two cases is the same, but the specific online units are different. In case 2, the units with higher sensitivity such as G39 and G38 are given priority to start up, and the total number of online hours for the units with lower sensitivity such as G34 and G36 are reduced.

4.2.2 Minimum frequency value

According to the unit commitment results obtained from the two cases, the simulation is carried out in PSASP, and the minimum frequency values at 24 times are compared, as shown in Figure 4.

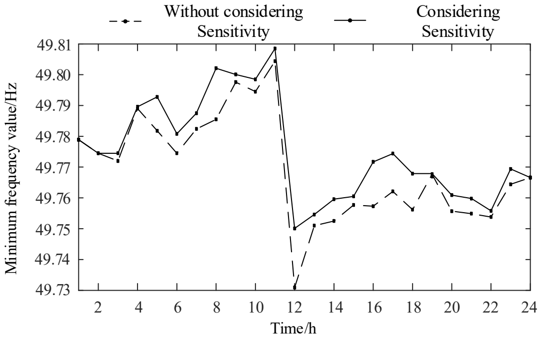

Fig. 4. Comparison of frequency nadir

We can see from Figure 4, after considering the sensitivity on the basis of frequency constraints, the minimum frequency has been improved, because case 2 allows the units with higher sensitivity to be started first, which providing better frequency support capability.

5 Conclusion

In order to deal with the system frequency problem caused by the high penetration of renewable power in the power system, this paper proposes a unit commitment model considering the sensitivity of synchronous generator adjustment coefficient. The main conclusions are as follows:

The sensitivity method is used to analyze the influence of different units' adjustment coefficient on the minimum frequency value, so as to characterize the frequency support capability of different units. The units with high sensitivity are more conducive to improving the system frequency stability. Add the sensitivity information into the unit commitment model on the basis of considering frequency constraints. Use the multi-objective optimization algorithm NSGA-II to solve the problem. The calculation and simulation results show that the minimum frequency value after disturbance can be further improved after considering sensitivity.

References

1. Z.Wang, L.L.Li, Z.H.Li, PSPC. J. 49, 5-73.(2021)
2. D.D.Li, Q.Liu,B.Xu, PSPC. J. 49, 24-33.(2021)
3. S.C.Li,B.J.Tian, H.Z.Li, PSPC. J. 50, 60-71.(2022)
4. C.Yan, Y.Tang, J.Dai, PCMP. J. 6, 1-13.(2021)
5. M.Malekpour, M.Zare, R. Azizipanah-Abarghooee. IET GENER TRANSM DIS. J. 14. (2020)
6. H.Li, Z.Lu, Y.Qiao, IEEE PES General Meeting 2020. C. (2020)
7. J.J.Rong, M.Zhou, G.Y.Li, Power System Technology. J. 46, 1335-1346. (2022)
8. J.X.OuYang, Y.F.Yuan, M.Y.Li, Power System Technology. J. 45, 2192-2201. (2021)
9. B.R.Cai, L.Yang, W.Huang, PSPC. J. 49, 169-177. (2021)
10. G.W.Cai, C.Zhong, G.Wu, AEPS. J. 45, 134-142. (2021)
11. X.L.Ge, Y.Liu, Y.Fu, Proceedings of the CSEE. J. 41, 4043-4058. (2021)
12. S.F.Guo, W.Li, S.S.Hu, Electric Power Engineering Technology. J. 39, 61-67. (2020)
13. X.F.Fan, X.Zhong, X.Q.Chang, PSPC. J. 43, 55-60. (2015)
14. F.Wang, H.F.Li, G.Y.Xu, PSPC. J. 48, 1-8. (2020)
15. F.Wang, G.Y.Xu, C.Shao, Electrical Measurement & Instrumentation. J. 1-8. (2022)
16. L.D.Zhao, X.C.Xing, Electrical Measurement & Instrumentation. J. 55, 31-35. (2018)

17. W.Ongsakul, N.Petcharaks, IEEE T POWER SYST. J. 19, 620-628. (2004)
18. B.Wang, D.Y.Yang, G.W.Cai, Power System Technology. J. 44, 2513-2519. (2020)
19. X.J.Pan, M.S.Fan, W.C.Zhang, ELECTRIC POWER. J. 53, 76-82. (2020)