Forest Chemicals Revew
www.forestchemicalsreview.com
ISSN: 1520-0191
July-August 2021 Page No. 1687-1701
Article History: Received: 12 May 2021 Revised: 25 June 2021 Accepted: 22 July 2021 Publication: 31 August 2021

Research on Setting Parameters of Generator Excitation System with Low Excitation Limit based on Heffron-Philips

Qian Huang[*], Nina Dai, Pengdan Ge, Lihong Xiang, Qingshan Xu, Guoping Lei
Electronic and Information Engineering School, Chongqing Three Gorges University, Wanzhou, Chongqing, 404100, China
*Corresponding Author.

Abstract:

In order to improve the reliability and stability of large electric generator, Based on the analysis of the Heffron-Philips mathematical model of generator excitation system, The article studied the theoretical method of parameter setting under different working conditions of low excitation limit link, constructed the single-machine infinite-bus system simulation model with excitation controller using PSCAD/EMTDC simulation software, The results of theoretical analysis of excitation system are verified. The variable low excitation limit parameters are simulated under different working conditions, Compared the dynamic response curves of excitation system regulated by different low excitation limiter, It provides a basis for the design and selection of low excitation limit of excitation system.

***Keywords**: Heffron-Philips, PSCAD/EMTDC, Low excitation limit, Parameter setting.*

I. INTRODUCTION

With the continuous expansion of power system scale and the extensive application of large-capacity units, The problem of power system stability becomes more and more serious, Therefore, the control performance of excitation system is required higher and higher; Examples of power grid failures at home and abroad show that: After the system failure, the generator excitation control system plays an important role in addition to the main voltage control, In the long course of failure and after failure, All kinds of excitation additional limit system will also play a role, and have a very important impact on the stability of the system [1]. The main function of the low excitation limit is to improve the high voltage and to provide the maximum possible reactive power support for the generator in emergency; However, there are few researches on the low excitation limit link, There is a lack of theoretical research on the parameter setting of the low excitation limit link model, Therefore, it is great significance to

Forest Chemicals Revew
www.forestchemicalsreview.com
ISSN: 1520-0191
July-August 2021 Page No. 1687-1701
Article History: Received: 12 May 2021 Revised: 25 June 2021 Accepted: 22 July 2021 Publication: 31 August 2021

study the influence of low excitation limit on the stable operation of power system when the power system fails [2].

In this paper, considered the Heffron-Philips model of single machine-infinite system, the self- excitation system is taken as the research object, the principle of parameter setting for low excitation limit is analyzed, the specific setting of different parameters under different working conditions is analyzed and the final setting value is obtained.

II. LOW EXCITATION LIMIT MODEL BASED ON HEFFRON-PHILIPS

The purpose of low excitation limit is to prevent the generator from losing its static stability due to the low excitation current [3].

2.1 Low Excitation Limit Model

The simplified block diagram of low excitation limit used in the simulation of this paper is shown in Figure 1.

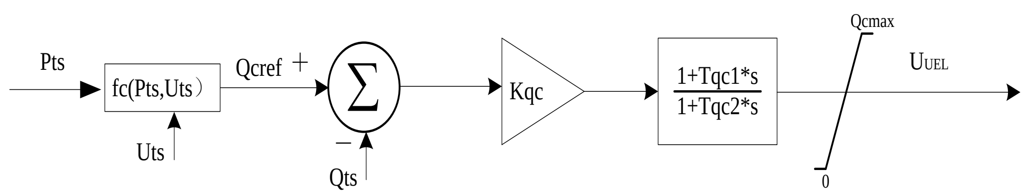
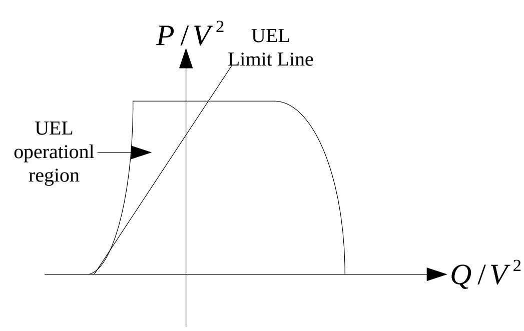


Fig 1: simplified block diagram of low excitation limit

The reactive power limit curve is approximately replaced by a line or circle, as shown in Figure 2.



Forest Chemicals Revew
www.forestchemicalsreview.com
ISSN: 1520-0191
July-August 2021 Page No. 1687-1701
Article History: Received: 12 May 2021 Revised: 25 June 2021 Accepted: 22 July 2021 Publication: 31 August 2021

Fig 2: Low excitation limit curve

Using PSCAD/EMTDC simulation software [4] to build the low excitation limit simulation model of Figure 3.

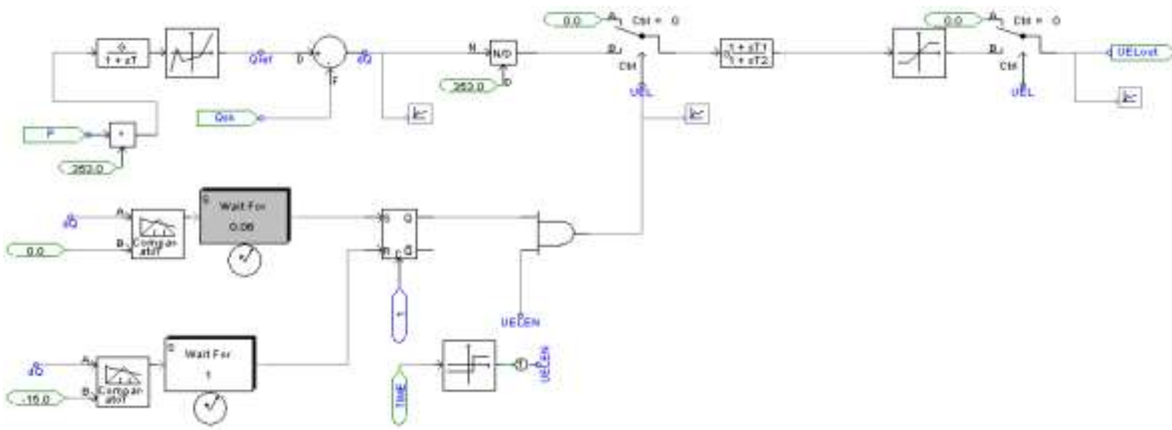


Fig 3: Low excitation limit simulation model

2.2 Single Machine-Infinite System

In the single-machine infinite system shown in Figure 4(The generator is connected to the infinite grid via a section of the line reactance for X_e) , Consider the Heffron-Philips model where the low excitation limit is output to the voltage superposition point.

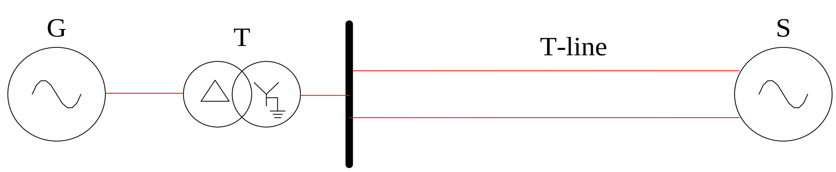


Fig 4: Single machine-infinite system

In the real power system dynamic analysis, the third-order model is usually used when the excitation system dynamic is considered [5]. The following is the mathematical model of the generator in dq coordinate system with small disturbance per unit:

Forest Chemicals Revew
www.forestchemicalsreview.com
ISSN: 1520-0191
July-August 2021 Page No. 1687-1701
Article History: Received: 12 May 2021 Revised: 25 June 2021 Accepted: 22 July 2021 Publication: 31 August 2021

$$\left.\begin{array}{l} d(\Delta\omega)/dt = (1/T_J)[\Delta P_T - V_{q0}\Delta I_q - V_{d0}\Delta I_d - I_{q0}\Delta V_q - I_{d0}\Delta V_d] \\ d(\Delta\delta)/dt = 2\pi f_0 \Delta\omega \\ d(\Delta E_q^{'})/dt = (1/T_{d0}^{'})[-\Delta E_q^{'} + \Delta E_{fd} - (X_d - X_d^{'})\Delta I_d] \\ \Delta E_q^{'} = \Delta V_q + X_d^{'}\Delta I_d - (E_{q0}^{'} - X_d^{'} I_{d0})\Delta\omega \\ 0 = \Delta V_d - X_q^{'}\Delta I_q - X_q^{'} I_{q0}\Delta\omega \end{array}\right\} \quad (1)$$

The voltage variation input to the AVR voltage superposition point and the low excitation limit input small disturbance can be expressed in the following form:

$$\Delta V = (V_{d0}/V_{t0})\Delta V_d + (V_{q0}/V_{t0})\Delta V_q \qquad (2)$$

$$\begin{bmatrix} \Delta\dot{\delta} \\ \Delta\dot{\omega} \\ \Delta\dot{E}_q^{'} \end{bmatrix} = \begin{bmatrix} 0 & 2\pi f_0 & 0 \\ -K_1/T_J & 0 & -K_2/T_J \\ -K_4/T_{d0}^{'} & 0 & -1/K_3 T_{d0}^{'} \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta E_q^{'} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1/T_{d0}^{'} \end{bmatrix} \Delta E_{fd} \qquad (3)$$

$$\Delta V = K_5 \Delta\delta + K_6 \Delta E_q^{'} \qquad (4)$$

$$\Delta S = K_7 \Delta\delta + K_8 \Delta E_q^{'} \qquad (5)$$

Collate the above formulas to get an extended H-P model diagram of Figure 5.

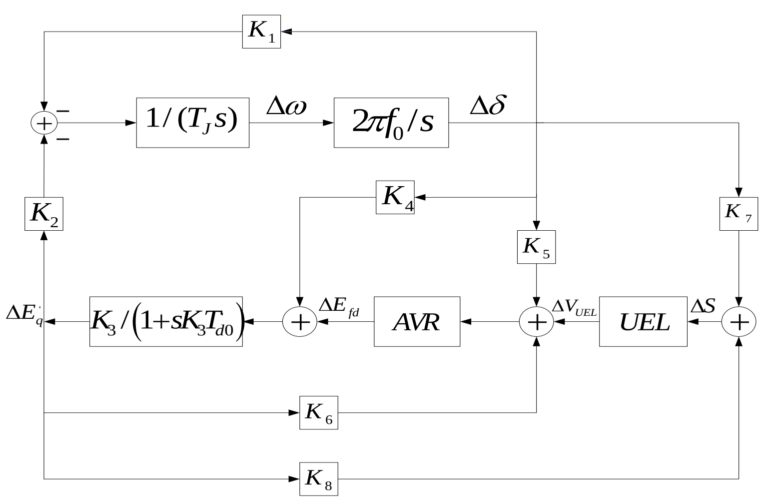


Fig 5: Extended H-P model

The input of the electric circuit is the difference between the additional excitation control $\square_{1ref}$ and the generator terminal voltage increment $\Delta\square_{\square}$, The output is the transient potential

Forest Chemicals Revew
www.forestchemicalsreview.com
ISSN: 1520-0191
July-August 2021 Page No. 1687-1701
Article History: Received: 12 May 2021 Revised: 25 June 2021 Accepted: 22 July 2021 Publication: 31 August 2021

increment $\Delta □_□'$ inside the generator, The increment of the internal potential multiplied by the constant $□_2$ becomes part of the electromagnetic power $\Delta □_□$(electrical Torque $\Delta □_□$), $\Delta □_□$ is composed of $□_5 \Delta\delta$ and $□_6 \Delta □_□'$. The various $X_□$ described above are the sum of the line reactance and the boost transformer reactance, The subscript 0 in the formula represents the steady-state initial value; $□_1$ and $□_2$ denote the influence of the generator's external power angle and the Q axis transient potential on the electromagnetic torque respectively; $□_3$ and $□_4$ denote the influence of the change of the external power angle and the q-axis transient potential on the q-axis potential; $□_5$ and $□_6$ denote the influence of the change of the external power angle and the q-axis transient potential on the terminal voltage[6].

2.3 H-P Model with Low Excitation Limit

To further simplify the analysis, the input points for both AVR and UEL are disconnected from the transfer function in Figure 5, The open-loop transfer functions of $\Delta V/\Delta □_{□□}$ and $\Delta S/\Delta □_{□□}$ are obtained:

$$\frac{\Delta V}{\Delta E_{fd}} = \frac{K_3 K_6 T_J S^2 + 2\pi f_0 (K_1 K_3 K_6 - K_2 K_3 K_5)}{K_3 T_{d0}' T_J S^3 + T_J S^2 + 2\pi f_0 K_1 K_3 T_{d0}' S + 2\pi f_0 (K_1 - K_2 K_3 K_4)} \tag{6}$$

$$\frac{\Delta S}{\Delta E_{fd}} = \frac{K_3 K_8 T_J S^2 + 2\pi f_0 (K_1 K_3 K_8 - K_2 K_3 K_7)}{K_3 T_{d0}' T_J S^3 + T_J S^2 + 2\pi f_0 K_1 K_3 T_{d0}' S + 2\pi f_0 (K_1 - K_2 K_3 K_4)} \tag{7}$$

Because $T_{d0}'^{\,2} >> (K_1 - K_2 K_3 K_4)$, $2\pi f_0 >> T_J$ and $\frac{2\pi f_0}{T_J} >> \frac{K_2 K_4}{K_1 T_{d0}'}$,Formula 6 can be reduced to $\frac{\Delta V}{\Delta E_{fd}} \cong \frac{K_6}{T_{d0}'}\left[\frac{S^2 + \frac{2\pi f_0 K_1}{T_J}(1 - \frac{K_2 K_5}{K_1 K_6})}{(S^2 + \frac{2\pi f_0 K_1}{T_J})(S + \frac{K_1 - K_2 K_3 K_4}{K_1 K_3 T_{d0}'})}\right]$, The extended H-P model [7]can be further reduced to Figure 6.

Forest Chemicals Revew
www.forestchemicalsreview.com
ISSN: 1520-0191
July-August 2021 Page No. 1687-1701
Article History: Received: 12 May 2021 Revised: 25 June 2021 Accepted: 22 July 2021 Publication: 31 August 2021

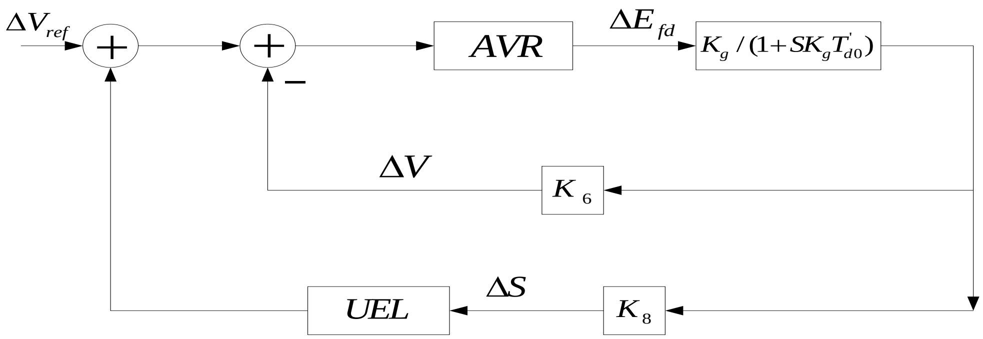


Fig 6: Simplified model considering low excitation limit

III. LOW EXCITATION LIMIT PARAMETER SETTING

The simulation uses the parameters shown in Table 1:

TABLE I . Basic parameters used in simulation

BASE RATING	GENERATOR	TRANSFORMER	WIRING
$S_{CN} = 350MW$	$X_d = 2.046$	$S_N = 530MW$	$X_L = 0.275$
$\cos\varphi = 0.85$	$X_q = 1.92$	$\text{n} = 20/525$	$\text{L} = 300$
$U_N = 20KV$	$X_d{}' = 0.298$	$U_K = 10\%$	
	$X_q{}' = 0.416$		
	$X_d{}'' = 0.177$		
	$X_q{}'' = 0.268$		
	$T_{d0}{}' = 6.1$		
	$T_{q0}{}' = 0.75$		
	$H = 4.15$		

If the generator is operating in the leading phase (P=0.77, Q= -0.2, $U_{\square 0} = 1$) , Combining the system parameters and the formulas mentioned in this paper, The expanded H-P model parameters can be derived as shown in Table 2.

TABLE II. Extended H-P model parameters

$U_{td} = 0.93$	$U_d = 1.01$	$K_1 = 1.05$	$K_5 = -0.06$
$U_{tq} = 0.37$	$U_q = 0.27$	$K_2 = 2.17$	$K_6 = 0.13$
$i_d = 0.64$	$E_Q = 1.59$	$K_3 = 0.21$	$K_7 = -0.52$
$i_q = 0.48$	$\text{Eq}' = 0.56$	$K_4 = 3.79$	$K_8 = 0.66$

Forest Chemicals Revew
www.forestchemicalsreview.com
ISSN: 1520-0191
July-August 2021 Page No. 1687-1701
Article History: Received: 12 May 2021 Revised: 25 June 2021 Accepted: 22 July 2021 Publication: 31 August 2021

With the parameters shown in TABLE2, Drawn the system's open loop transfer function block diagram is shown in Figure 7 and the corresponding baud diagram is shown in Figure 8.

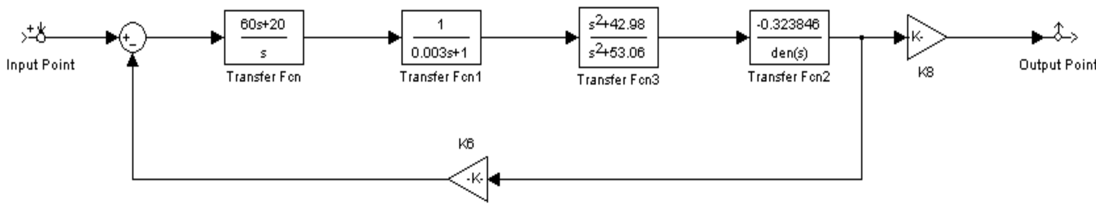


Fig 7: Block diagram of open-loop transfer function

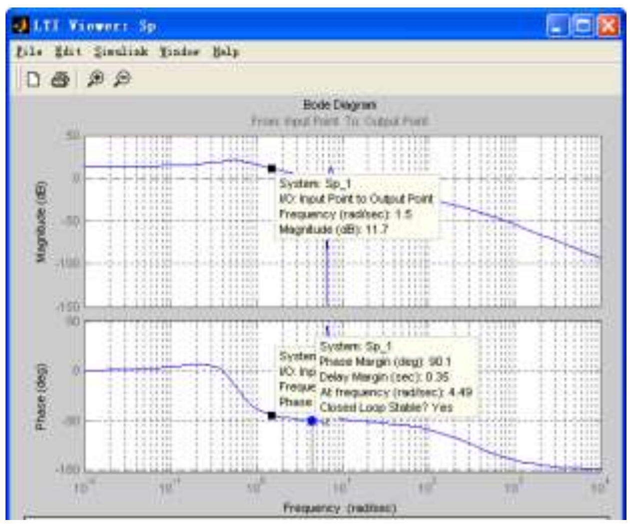


Fig 8: Baud Diagram of open-loop transfer function

In order to achieve good coordination with PSS, the new cut-off frequency compensation should be less than 3 rad/sec, Phase frequency margin of at least 40 degrees, Amplitude frequency margin of at least 6 dB. Calculated the time parameters of the low excitation link under different proportional gain, Different lead-lag link time parameter($K = 10$, $\square_1 = 0.4$, $\square_2 = 29$ and $K = 10$, $\square_1 = 0.5$, $\square_2 = 33$), When the terminal voltage is given 10% step, can get the simulation waveform shown in Figure 9.

Forest Chemicals Revew
www.forestchemicalsreview.com
ISSN: 1520-0191
July-August 2021 Page No. 1687-1701
Article History: Received: 12 May 2021 Revised: 25 June 2021 Accepted: 22 July 2021 Publication: 31 August 2021

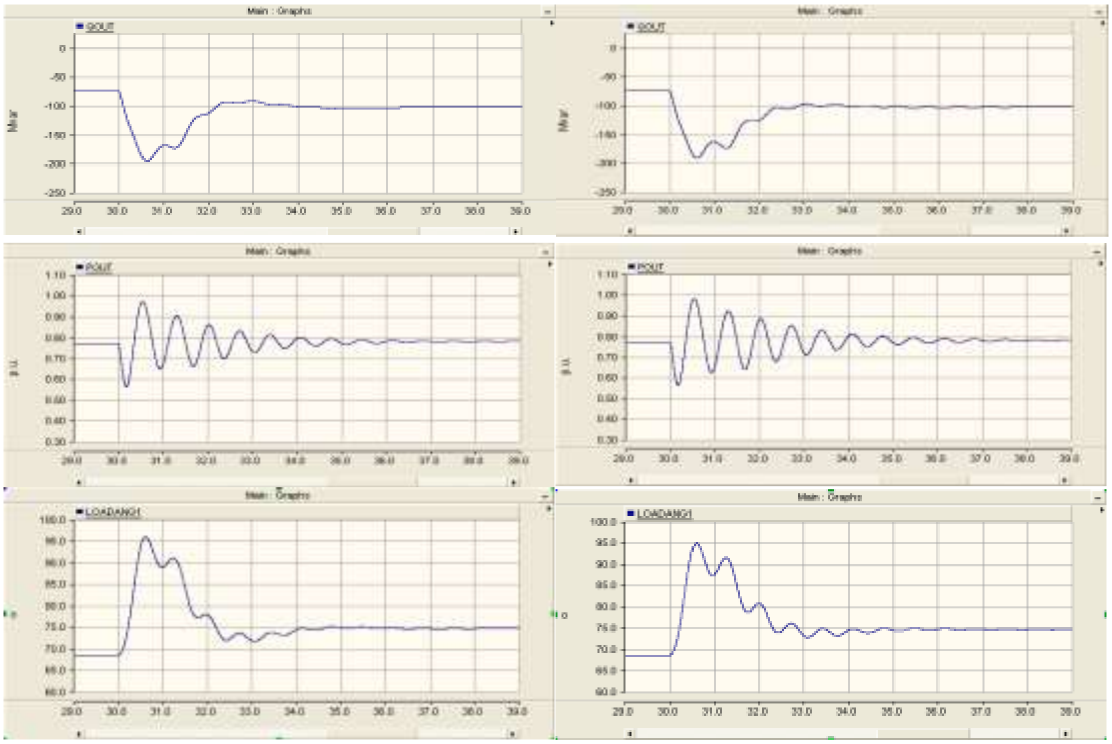


Fig 9: Comparison of simulation waveforms

The simulation parameters corresponding to the same time constant and different proportional gain can also be obtained, as shown in Table3.

TABLE III. Simulation comparison

K	LOADANG1(max)	QOUT(min)	T_r	D
5	69.056	−74.346	0.701	0.067
10	67.912	−66.643	0.643	0.054
20	66.982	−60.142	0.582	0.041
30	66.593	−59.092	0.415	0.024

The selected parameters of the low excitation limit link should make the ability of the reactive power output to restrain the oscillation meet the requirements. Simulation and theoretical analysis show that the dynamic and steady-state characteristics of the whole system are the best, when the phase angle margin of compensation is 75 degrees, The cutoff frequency is between 1.5 rad/sec and 3.0 rad/sec; And low excitation limit operation can play a better effect, the system will not oscillate, and as smooth as possible rapid recovery of reactive power

Forest Chemicals Revew
www.forestchemicalsreview.com
ISSN: 1520-0191
July-August 2021 Page No. 1687-1701
Article History: Received: 12 May 2021 Revised: 25 June 2021 Accepted: 22 July 2021 Publication: 31 August 2021

output, enhance the generator power angle stability.

IV. PATAMETER ANALYSIS OF DIFFERENT WORKING CONDITIONS

Analyzed the adaptability of the low excitation limit under different working conditions, According to the specific value of a parameter, given the corresponding parameter adjustment strategy. The method of low excitation gain control with variable parameters can effectively reduce the power system oscillation and enhance the stability of the power system.

4.1 Basic Parameter Setting

4.1.1 Gain parameter

Keep the parameters $\square_1 = 0.9$, $\square_2 = 30$ constant, the regulation K varies from 5 to 15, When $P = 0.8\square.\square$, $Q = -80\square\square\square\square$, The simulation results are shown in Figure 10.

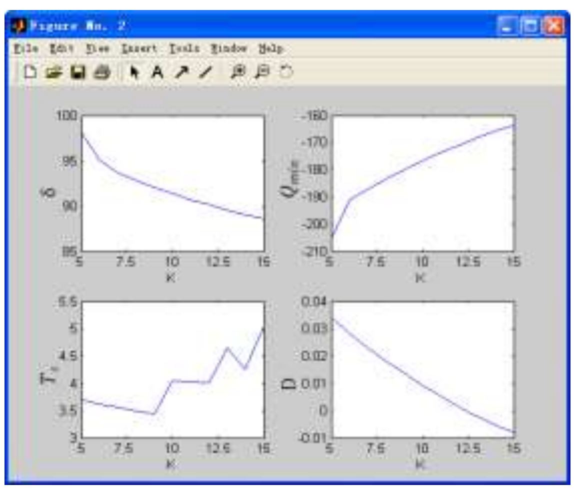


Fig 10: Waveform to the change of gain k

As can be seen from the Figure 10, when K is small, the maximum transient value of the generator power angle is 98 degree, and the minimum reactive power output is -205 Mvar, When K is about 12, the system is in critical damping state, so it is better to consider K = 10 as a compromise.

4.1.2 Lead time constant

Keep the parameters $K = 10$, $T_2 = 30$ constant, the regulation T_1 varies from 0.3 to 1,

Forest Chemicals Review
www.forestchemicalsreview.com
ISSN: 1520-0191
July-August 2021 Page No. 1687-1701
Article History: Received: 12 May 2021 Revised: 25 June 2021 Accepted: 22 July 2021 Publication: 31 August 2021

When $\mathrm{P}=0.8p.u$, $\mathrm{Q}=-80Mvar$, The simulation results are shown in Figure 11.

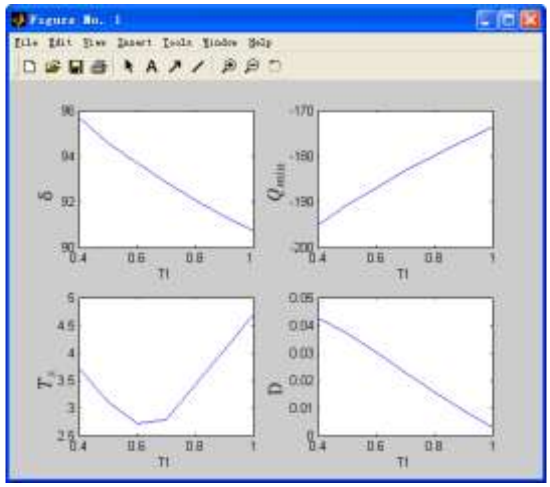
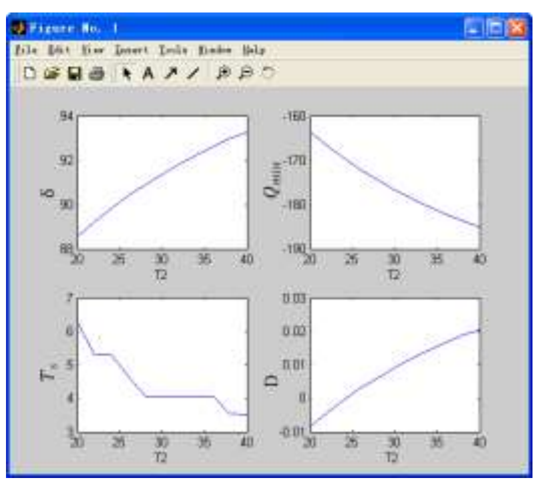


Fig 11: Waveform to the change of Lead time constant T_1

As can be seen from the Figure 11, when T_1 is small, the maximum transient value of the generator power angle is 97 degree, and the minimum reactive power output is -199.5 Mvar, When T_1 is about 1, the system is in critical damping state, so it is better to consider T_1=0.9 as a compromise.

4.1.3 Lag time constant

Keep the parameters $\mathrm{K}=10$, $T_1=0.9$ constant, the regulation T_2 varies from 20 to 40, When $\mathrm{P}=0.8p.u$, $\mathrm{Q}=-80Mvar$, The simulation results are shown in Figure 12.



Forest Chemicals Revew
www.forestchemicalsreview.com
ISSN: 1520-0191
July-August 2021 Page No. 1687-1701
Article History: Received: 12 May 2021 Revised: 25 June 2021 Accepted: 22 July 2021 Publication: 31 August 2021

Fig 12: Waveform to the change of Lead time constant T_2

As can be seen from the Figure 12, when T_2 is large, the maximum transient value of the generator power angle is 93 degree, and the minimum reactive power output is -185 Mvar, When T_2 is about 25, the system is in critical damping state, so it is better to consider T_2=30 as a compromise. The parameters of the low excitation limit link are $10\frac{1+0.9S}{1+30S}$.

4.2 Parameter Setting in Different Working Conditions

4.2.1 Gain parameter

Keep the parameters $\mathrm{Q} = -80Mvar, T_1 = 0.9,\ \ T_2 = 30$ constant, When the active power is different, the waveform diagram corresponding to the gain change is shown in Figure13.

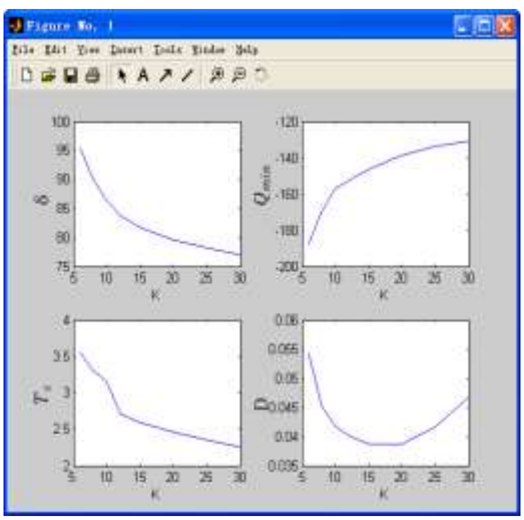


Fig 13(a): Active power 0.7p.u

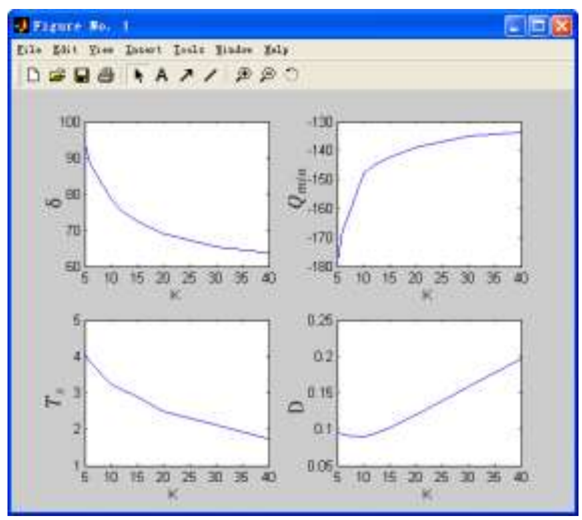


Fig 13(b): Active power 0.4p.u

As can be seen from the Figure 13(a), when active power is about 0.7p.u and K is small, the maximum transient value of the generator power angle is 95 degree, and the minimum reactive power output is -187 Mvar, so it is better to consider K=10 as a compromise. But as can be seen from the Figure 13(b), when active power is about 0.4p.u, the maximum transient value of the generator power angle is 93.6 degree, and the minimum reactive power output is -178 Mvar, If the feedback gain is too large, the disturbance will be amplified and the control value will fluctuate. The value of K should not exceed 20, so it is better to consider K=15 as a

Forest Chemicals Revew
www.forestchemicalsreview.com
ISSN: 1520-0191
July-August 2021 Page No. 1687-1701
Article History: Received: 12 May 2021 Revised: 25 June 2021 Accepted: 22 July 2021 Publication: 31 August 2021

compromise. Therefore, the value of K should be considered to meet the requirements of different working conditions.

The parameters of gain K have obvious influence on the step characteristic of the phase advection, The higher the K, the faster the action, the smaller the lowest reactive power, the shorter the time to adjust to the set value, but the system damping ratio is weaker. Compared to the K, The parameters of $\square_1$ and $\square_2$ have a great influence on the dynamic characteristics of the regulating process.

4.2.2 Lead time constant

Keep the parameters $Q = -80\square\square\square\square$, $K = 10$, $\square_2 = 30$ constant, When the active power is different, the waveform diagram corresponding to the lead time constant change is shown in Figure14.

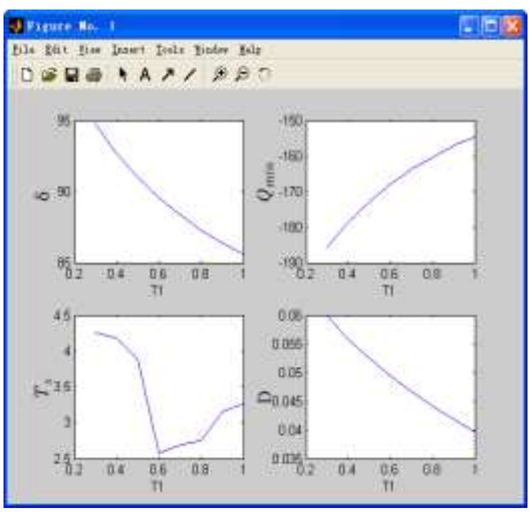


Fig 14(a): Active power 0.7p.u

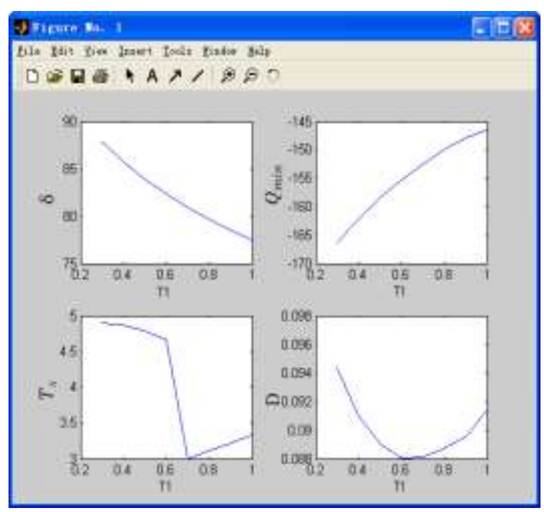


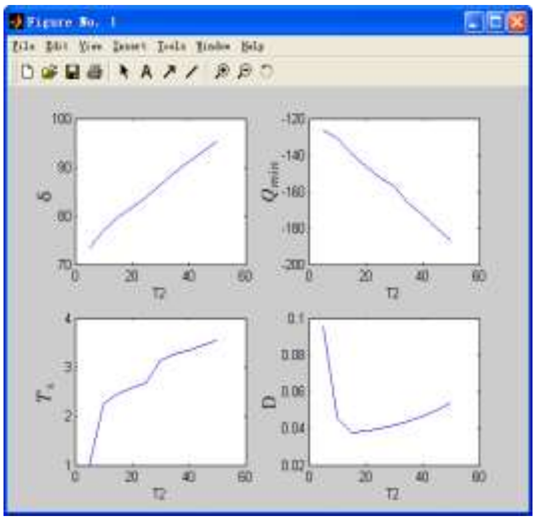
Fig 14(b): Active power 0.4p.u

As can be seen from the Figure 14(a), when active power is about 0.7p.u and $\square_1$ is small, the maximum transient value of the generator power angle is 92 degree, and the minimum reactive power output is -178.6 Mvar, so it is better to consider $\square_1$=0.9 as a compromise. But as can be seen from the Figure 14(b), when active power is about 0.4p.u, the maximum transient value of the generator power angle is 87.8 degree, and the minimum reactive power output is -166 Mvar, so it is better to consider $\square_1$=0.4 as a compromise.

4.2.3 Lag time constant

Forest Chemicals Revew
www.forestchemicalsreview.com
ISSN: 1520-0191
July-August 2021 Page No. 1687-1701
Article History: Received: 12 May 2021 Revised: 25 June 2021 Accepted: 22 July 2021 Publication: 31 August 2021

Keep the parameters $Q = -80Mvar$, $K = 10$, $T_1 = 0.9$ constant, When the active power is different, the waveform diagram corresponding to the lag time constant change is shown in Figure15.



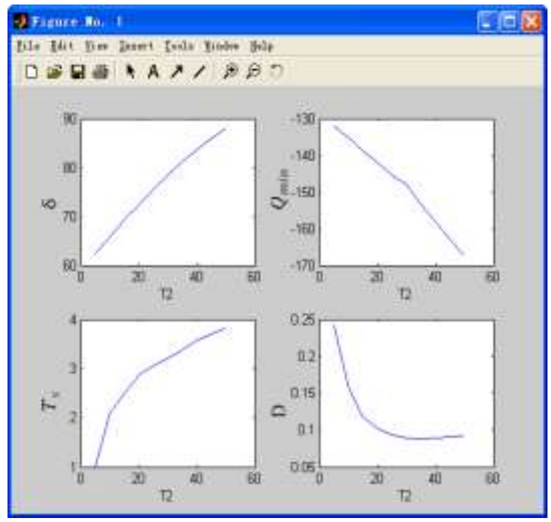


Fig 15(a): Active power 0.7p.u Fig 15(b): Active power 0.4p.u

As can be seen from the Figure 15(a), when active power is about 0.7p.u and $\square_2$ is large, the maximum transient value of the generator power angle is 95 degree, and the minimum reactive power output is -187Mvar, so it is better to consider $\square_2$=30 as a compromise. But as can be seen from the Figure 15(b), when active power is about 0.4p.u, the maximum transient value of the generator power angle is 88 degree, and the minimum reactive power output is -167 Mvar, so it is better to consider $\square_2$=10 as a compromise.

The results show that K and $\square_2$ have concave trough when p = 0.7, but $\square_1$ has concave trough when p = 0.4, When this phenomenon is taken into account, the optimal effect of parameter output can be obtained under the current operating conditions and can be set unchanged.

V. CONCLUSION

With the development of power grid structure, Starting from the principle of low excitation limit, Study the setting process of gain, lead time constant and lag time constant of generator with low excitation limit, Adjust the variable parameters under different working conditions, Verify the correctness of the method by example and came to the following conclusion:

1.There is a problem in keeping the parameters of the low excitation limit link of the generator excitation system unchanged, which can't adapt to different system conditions.

2. Starting with the Heffron-Philips mathematical model of generator excitation system, extended the simplified H-P model and gain the method of parameters setting of low excitation limit link.

3. Change the parameters of low excitation limit under different working conditions and simulation results show that the control strategy is effective.

ACKNOWLEDGEMENTS

This research was supported by Scientific Research Project of Chongqing Education Commission ("Research on the key technology of flexible peak load regulation based on peak shaving and valley filling strategy ", Grant No. KJQN201901213), National Natural Science Foundation of China (Grant No. cstc2021jcyj-msxm2025), Scientific Research Project of Chongqing Education Commission(Grant No. KJZD-K201901203), Chongqing University Innovation Research Group(Grant No. CXQT20024)

REFERENCES

[1] Zhou CP, Wang Z, Ju P, Gan DQ (2020). High-voltage Ride Through Strategy for DFIG Considering Converter Blocking of HVDC System. Journal of Modern Power Systems and Clean Energy, 03: 139-144.

[2] Grondin R, Kamwa I, Trudel G (2003). Modeling and closed-loop validation of a new PSS concept' the multi-hand PSS. IEEE Power Engineering Society General Meeting 'Toronto' Canada': 1804-1809.

[3] Zhao H, Zhou CH (2013). Matching of Generator Low Excitation Limit Setting and Loss-of-Excitation Protection between Different Coordinates. Applied Mechanics and Materials: 448–453.

[4] Zhao F, Wu T, Xie X (2018). Study on the influence of Auxiliary Control Function of Generator excitation on the dynamic reactive power support capability of UHV DC feed terminal. Grid Technology, 42:2262–2272.

[5] Qiu L, Wang KW (2011). MULTI-FREQUENCY PSS structure design and parameter coordination. Power system protection and control, 39: 102-107.

[6] Li JC (2017). Design and Application of Modern Synchronous Generator Excitation Systems. China: China Electric Power Pub. Co. ISBN9787512396869.

Forest Chemicals Revew
www.forestchemicalsreview.com
ISSN: 1520-0191
July-August 2021 Page No. 1687-1701
Article History: Received: 12 May 2021 Revised: 25 June 2021 Accepted: 22 July 2021 Publication: 31 August 2021

[7] Meng C (2018). Study on the influence of generator excitation limit on power system security and stability. Dissertation. Graduate degree in Electrical Engineering. North Electric Power University, China:75.