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Analysis of Damping of Excitation System with Direct Current Energy

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Abstract

In order to explain the mechanism of the excitation part of the low-frequency oscillation, an equivalent circuit of the generator excitation part is constructed based on the sixth-order model of the generator. Through the equivalent circuit of the excitation part of the generator, the energy flow of the excitation part of the generator is constructed. Through TLS-ESPRIT technique, DC power can be obtained. DC energy is obtained through DC power integration.The generator excitation part injects the positive and negative DC energy of the system to determine the positive or negative contribution of the excitation control system to the damping of the system oscillation. The simulation results verify the validity of the conclusions and lay the foundation for the direct current energy analysis of excitation damping from the equivalent circuit.

Keywords

Sixth Order Generator Model; Electrical Circuits; DC Energy; Damping.

1. Introduction

Studies have shown that low-frequency oscillations in power systems threaten the safe and stable operation of interconnected large-scale power grids. If the influence of excitation damping on system oscillation can be analyzed clearly, oscillation accidents will be reduced. In the problem of low-frequency oscillations in power systems, the energy function method has made some progress.

A low-frequency oscillation analysis and oscillation source location method based on oscillation energy are proposed in [1-3]. In [4],the paper analyzes the internal energy structure of the generator based on Hamilton. A phenomenon is discovered in [5-6]. There is a relationship between low frequency oscillation energy and damping torque. Power system energy function construction method based on elastic mechanics topology mapping, and used for low-frequency oscillation energy analysis [7-8]. Based on the sixth-order generator model, the structure-maintaining energy function is established [9].

This paper uses a sixth-order generator model to analyze the problem in more detail and accuracy. Then through the equivalent circuit, the clear energy flow can be viewed more directly. In the past, the positive and negative damping was judged by the oscillation energy, but the oscillation energy contains AC energy as well as DC energy. In this paper, the DC energy is decomposed, and it is more accurate to judge the positive and negative damping through the DC energy.

2. Sixth-order generator model

The sixth-order model of the generator is as follows:

$$\dot{\delta} = \Delta\omega \tag{1}$$

$$M\Delta\dot{\omega} = P_m - P_e - D\Delta\omega \tag{2}$$

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$$T'_{do}\dot{E}'_q = E_f - E'_q - \frac{x_d - x'_d}{x'_d - x''_d}(E'_q - E''_q) \tag{3}$$

$$T'_{qo}\dot{E}'_d = -E'_d - \frac{x_q - x'_q}{x'_q - x''_q}(E'_d - E''_d) \tag{4}$$

$$T''_{do}\dot{E}''_q = E'_q - E''_q - (x'_d - x''_d)i_d \tag{5}$$

$$T''_{qo}E''_d = E'_d - E''_d + (x'_q - x''_q)i_q \tag{6}$$

When neglecting the stator resistance, the voltages of the d-axis and q-axis are:

$$u_d = E''_d + x''_q i_q \tag{7}$$

$$u_q = E''_q - x''_d i_d \tag{8}$$

Where: δ rotor angle of generator; $\Delta\omega_r = \omega_r - \omega_{ref}$, rotor angular velocity and reference velocity; M inertia constant of generator; P_m generator mechanical power; P_e electrical real power; D damp constant of generator; E_f field voltages; T'_{do} d-axis open circuit transient; T''_{do} sub transient time constants; T'_{qo} q-axis open circuit transient; T''_{qo} sub transient time constants; E'_q transient EMFs of d-axis; E'_d transient EMFs of q-axis; i_d currents of d-axis armature; i_q urrents of q-axis armature; x_d, synchronous reactances of d-axis, x'_d transient reactances of d-axis; x''_d sub transient of d-axis; $x_q$synchronous reactances of q-axis; x'_qtransient reactances of q-axis; x''_q sub transient reactances of q-axis; E''_d sub transient EMFs of d- axis; E''_q sub transient EMFs of q-axis; u_d voltages of d-axis armature; u_q voltages of q-axis armature.

3. Circuit diagram and energy flow of generator d-axis excitation part

Through formulas (3), (5), (8), the circuit diagram of the excitation part of the sixth-order model of the generator is obtained. See Fig. 1:

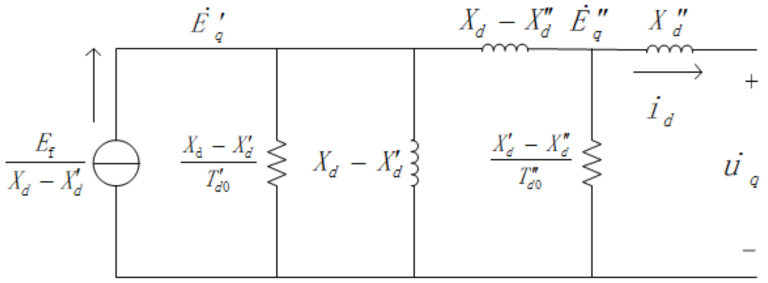

Fig. 1 Electrical circuits

The above picture can be regarded as a (generalized) current source$\frac{E_f}{x_d - x'_d}$, resistance$\frac{x_d - x'_d}{T'_{\mathrm{do}}}$、$\frac{x'_d - x''_d}{T''_{\mathrm{do}}}$, inductance$x_d - x'_d$,$x'_d - x''_d$,$x''_d$.

voltage of current source $\frac{E_f}{x_d - x'_d}$ is $\dot{E}'_q$, voltage of resistance $\frac{x_d - x'_d}{T'_{\mathrm{do}}}$ is $\dot{E}'_q$, flux linkage of inductance $x_d - x'_d$ is E'_q, flux linkage of inductance $x'_d - x''_d$ is $E'_q - E''_q$, voltage of resistance $\frac{x'_d - x''_d}{T''_{\mathrm{do}}}$ is $\dot{E}''_q$, current of inductance x''_d is i_d.

4. Obtain DC energy

The low-frequency oscillation signal of the power system can be expressed as:

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$$X(t)=\sum_{m=1}^{m=Q} A_m e^{\sigma_m t} cos(2\pi f_m t+\varphi_m) \tag{9}$$

Where Q is the number of assumed signal modes, A_m is the amplitude, σ_m is the attenuation factor, f_m is the frequency, φ_m is the initial phase.

From Part 3, the current injected into the power system by the excitation part is $\frac{E_f}{x_d-x_d'}$, voltage is $\dot{E}_q'$, power is $\frac{E_f}{x_d-x_d'}\dot{E}_q'$, energy is $\int\frac{E_f}{x_d-x_d'}dE_q'$.

Therefore, the corresponding voltage and current modes of the excitation part are identified through the TLS-ESPRIT technique. Then multiply each mode combination to get the power. Finally, the DC power is obtained through screening, and the DC power is integrated to obtain the DC energy. Details as follows:

Identify the current first:

$$i(t)=\frac{E_f}{x_d-x_d'}(t)=\sum_{m=1}^{m=Qi} A_{mi} e^{\sigma_{mi} t} cos(2\pi f_{mi} t+\varphi_{mi}) \tag{10}$$

Then identify the voltage:

$$u(t)=\dot{E}_q'(t)=\sum_{m=1}^{m=Qu} A_{mu} e^{\sigma_{mu} t} cos(2\pi f_{mu} t+\varphi_{mu}) \tag{11}$$

So power:

$$\begin{aligned} p(t)&=i(t)u(t)=\frac{E_f}{x_d-x_d'}(t)\dot{E}_q'(t)\\ &=\sum_{m=1}^{m=Qi} A_{mi} e^{\sigma_{mi} t}\cos(2\pi f_{mi} t+\varphi_{mi})\sum_{m=1}^{m=Qu} A_{mu} e^{\sigma_{mu} t}\cos(2\pi f_{mu} t+\varphi_{mu}) \end{aligned} \tag{12}$$

After formula transformation:

$$\begin{aligned} p(t)=\sum_{m=1}^{m=Qi}\sum_{m=1}^{m=Qu}\frac{1}{2}A_{mi}A_{mu}e^{(\sigma_{mi}+\sigma_{mu})t}[&\cos(2\pi(f_{mi}+f_{mu})t+\varphi_{mi}+\varphi_{mu})\\ &+\cos(2\pi(f_{mi}-f_{mu})t+\varphi_{mi}-\varphi_{mu}) \end{aligned} \tag{13}$$

Equation (13) shows that the frequency f_p of the power mode is composed of $f_{mi}+f_{mu}$ or $f_{mi}-f_{mu}$. In order to get the DC power, it is necessary to filter out the high frequency in the power mode. Of course, it is possible to filter out the modes with smaller amplitudes that have less impact on the overall DC power.

Finally, DC power is obtained:

$$P(t)=\sum_{m=1}^{m=QP} A_{mP} e^{\sigma_{mP} t}\cos(2\pi f_{mP} t+\varphi_{mP}) \tag{14}$$

DC energy is DC power integral:

$$W(t)=\int P(t)\,dt=\int\sum_{m=1}^{m=Q} A_{mP} e^{\sigma_{mP} t}\cos(2\pi f_{mP} t+\varphi_{mP})\,dt \tag{15}$$

When the system is disturbed, it is equivalent to injecting disturbance energy into the stable system from the outside world. The faster the disturbance energy is consumed, the faster the oscillation can be calmed down. When subjected to external disturbances, the smaller the DC energy provided by the excitation system, the faster the system consumes the disturbance energy, that is, the greater the damping provided by the excitation part.

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5. Test result

Build a One machine infinite bus system in BPA software, and the system parameters can be found in [10]. Speed control system is not used, generator damping D=0. The excitation system is an EA model provided by BPA, and its parameters are $T_R = 0.05, T_A = 0.055$, $T_{A1} = 0$, $V_{RMAX\ MULT} = -1$, $K_E = 0$, $T_E = 0.36$, $S_{E.75MAx} = 0.094$, $S_{EMAx} = 0.241$, $E_{FDMIN} = -3.5$, $E_{FDMAX} = 3.5$, $K_F = 0.125$, $T_F = 1.8$. By changing the voltage regulator gain KA, the damping of the excitation part is changed. The K_A value is K_A=10, K_A=50, K_A=80.

Make the system oscillate with a short-term fault, and measure the field voltage E_f and the transient EMFs of d-axis E_q'. Then through the previous part 3, get the DC power. DC power integration to get DC energy, compare the magnitude. The greater the DC energy provided by the excitation part, the smaller the damping. The specific results are as follows:

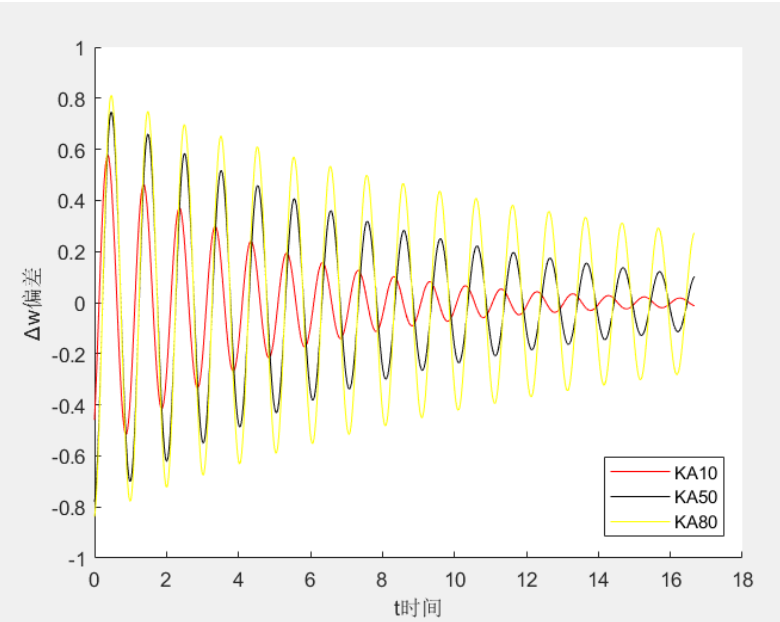

Fig. 2 Generator speed deviation

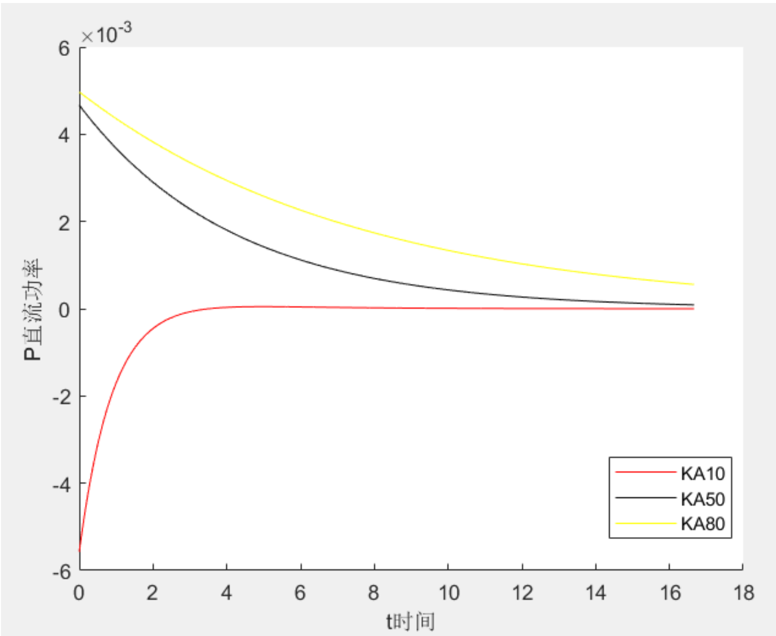

Fig. 3 DC power

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As can be seen in Figure 2, when the excitation system K_A=10, K_A=50, K_A=80, the oscillation amplitude becomes larger. So the damping provided by the excitation system becomes smaller.

It can be seen from Figure 3 that $P(K_A10)<0<P(K_A50)<P(K_A80)$. DC power integral is DC energy. So you can get $W(K_A10)<0<W(K_A50)<W(K_A80)$. Because K_A80 has the largest DC energy, the damping is the smallest.

Figure 2 and Figure 3, the results are the same, so we verify the feasibility of judging by DC energy.

6. Conclusion

Based on the energy method, this article combines the circuit diagram with the TLS-ESPRIT technique. After screening, the DC component of the oscillation energy after the excitation system is disturbed is obtained. The magnitude of the DC energy of the excitation system just reflects the magnitude of the damping provided by the excitation system. This method has also been verified in the simulation.

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