The analysis of power system stabilizer based on Heffron–Philips model

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Abstract. With the size of power system increasing, low frequency oscillation has been the danger of power system and the most important factor of power transmission capacity constraints. Usually power system stabilizer is configured to suppress low frequency oscillation. Introduced the development and type of PSS, Especially the PSS4B model, Presented the function and the effect of parameters to damping the low frequency oscillation. Analysis the reason of low frequency oscillation in power system which applies the fast response excitation regulator theoretically using the one machine-infinite bus system small disturbance linear model (Heffron–Philips model). The principle of PSS damps low frequency oscillation-phase compensation. Prove that PSS has a good effect on low frequency oscillation.

Key words. Power system stabilizer (PSS), Heffron–Philips model, low frequency oscillation, excitation system..

1. Introduction

In recent years, Fast Response Excitation System apply the majority of places in our world, Although the imbalance between power production and consumption area is solved, however produce the damping of power system [1], thus leading to low frequency oscillation [2]. According to the filed operation experience and a large number of simulation results, spontaneous oscillation often exists in a very low frequency of regional power grid, if the system cannot provide damping, suppress the low frequency oscillation, Will seriously affect the stability of the system, and even cause a large area outage [3]. Among the measures to suppress low frequency oscillation, Power System Stabilizer is one of the most widely accepted measure [4].

Based on the consideration of Heffron–Philips model for One Machine-Infinity Bus [5], analyzed the reason of low frequency oscillation caused by fast-response excitation system and the basic principle of positive damping for power system stabilizer, mainly discuss the basic principle and characteristics of the new PSS4B

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model.

2. Analysis of low frequency oscillation based on Heffron–Philips model

In Fig. 1 shows the one machine-infinity bus, considering the generator speed is small changes with small perturbations. Also ignores the effect of damping winding function as well as the DC component of stator resistance and stator current. The Parker equation is reduced to the following form

$$U_{\text{td}} = -\varphi q = X_{\text{q}} i_{\text{q}} \,, \tag{1}$$

$$U_{\text{tq}} = E_{\text{q}} - x_{\text{d}} i_{\text{d}} \,, \tag{2}$$

$$E_{\text{q}}^{'} = E_{\text{q}} - \left(x_{\text{d}} - x_{\text{d}}^{'} \right) i_{\text{d}} \,, \tag{3}$$

$$\frac{\mathrm{d} E_{\text{q}}^{'}}{\mathrm{d} t} = \frac{1}{T_{\text{d0}}^{'}} \left(E_{\text{fd}} - E_{\text{q}} \right) \,. \tag{4}$$
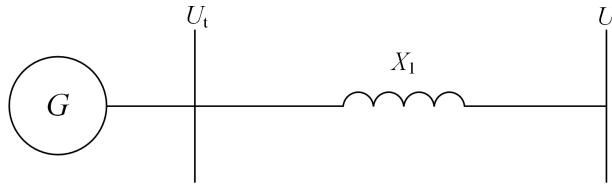

Fig. 1. One machine-infinity bus model

By studying the effect of active micro oscillation, the following four expressions can be derived

$$\Delta M_{\text{e}} = K_1 \Delta \delta + K_2 \Delta E_{\text{q}}^{'} \,, \tag{5}$$

$$\Delta E_{\text{q}}^{'} = \frac{K_3}{1 + T_{\text{d0}}^{'} K_3 S} \Delta E_{\text{fd}} - \frac{K_3 K_4}{1 + T_{\text{d0}}^{'} K_3 S} \Delta \delta \,, \tag{6}$$

$$\Delta U_{\text{t}} = K_5 \Delta \delta + K_6 \Delta E_{\text{q}}^{'} \,, \tag{7}$$

$$\Delta \delta = \frac{W_0}{T_{\text{J}} S^2} \left(\Delta M_{\text{m}} - \Delta M_{\text{e}} \right) \,. \tag{8}$$

The following expression of K_1 to K_6

$$K_1 = \frac{x_{\text{q}} - x_{\text{d}}^{'}}{x_{\text{d}}^{'} + x_1} i_{\text{q0}} U \sin \delta_0 + \frac{U \cos \delta_0}{x_{\text{q}} + x_1} E_{\text{Q0}} \,, \tag{9}$$

$$K_2 = \frac{x_{\mathrm{q}} + x_1}{x_{\mathrm{d}} + x_1} i_{\mathrm{q}0} , \tag{10}$$

$$K_3 = \frac{x'_{\mathrm{d}} + x_1}{x_{\mathrm{d}} + x_1} , \tag{11}$$

$$K_4 = \frac{x_{\mathrm{d}} - x'_{\mathrm{d}}}{x'_{\mathrm{d}} + x_1} U \sin \delta_0 , \tag{12}$$

$$K_5 = \frac{u_{\mathrm{td}0}}{U_{\mathrm{t}0}} \frac{x_{\mathrm{q}}}{x_{\mathrm{q}} + x_1} U \cos \delta_0 - \frac{u_{\mathrm{tq}0}}{U_{\mathrm{t}0}} \frac{x'_{\mathrm{d}}}{x'_{\mathrm{d}} + x_1} U \sin \delta_0 , \tag{13}$$

$$K_6 = \frac{u_{\mathrm{tq}0}}{U_{\mathrm{t}0}} \frac{x_1}{x'_{\mathrm{d}} + x_1} , \tag{14}$$

where ΔM_{e} is the electromagnetic torque of generator, T_{j} is the inertia time constant, ΔM_{m} is the mechanical torque of prime mover, K_1 is the external angle of generator, K_2 is the effect of transient potential on electromagnetic torque, K_3 is the effect of external angle change on q axis electric potential, K_4 is the effect of transient potential change on q axis electric potential, K_5 is the effect of external angle change on generator voltage, K_6 is the relationship between q axis transient potential and generator voltage [6].

We can see from the expression of K_5, the response is the relationship between generator voltage and generator power angle when the generator rotor is in synchronous small oscillation. Self-shunt excitation system takes the generator voltage feedback as the main basis, thus connected the problem of the excitation regulator with the swing of the generator rotor.

As can be seen from the expression of K_4 and K_5, the influence of the generator electromagnetic torque is mainly caused by the effect of the transient potential of the q axis. However, due to the electromagnetic inertia, the change of electromagnetic torque always lags behind the change of generator power angle, this is the root cause of negative damping.

The above expressions constitute mathematical model of synchronous machine shown in Fig. 2.

As can be seen from the Fig. 2, the excitation regulator is to change the torque $\Delta M_{\mathrm{e}2}$ by changing the $\Delta E'_{\mathrm{q}}$, that is torque $\Delta M_{\mathrm{e}2}$ is generated by the change of $\Delta \delta$, as shown in Fig. 3.

Ignore armature reaction, for fast response excitation system, the transfer function can be expressed as the following expression

$$G_{\mathrm{e}} = \frac{\Delta E_{\mathrm{fd}}}{\Delta U_{\mathrm{t}}} = \frac{K_{\mathrm{A}}}{1 + T_{\mathrm{E}} S} . \tag{15}$$
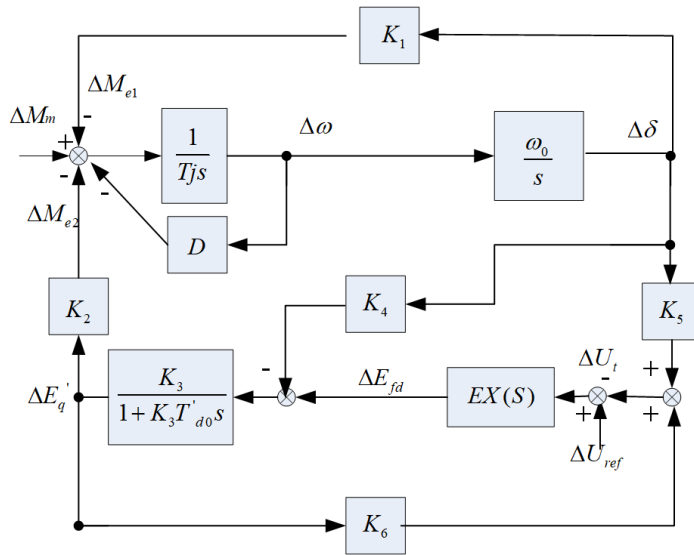
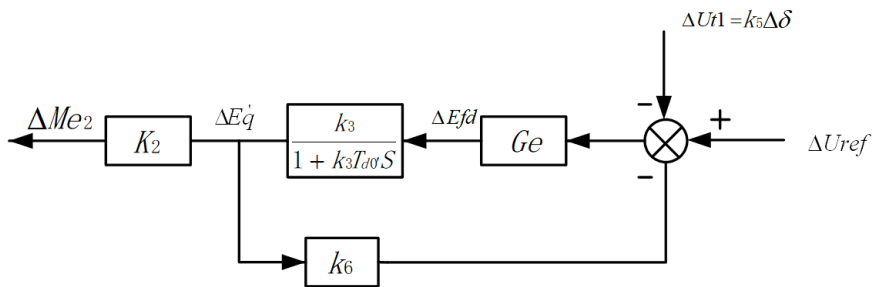Fig. 2. Mathematical model of synchronous machine

Fig. 3. Block diagram of excitation control system

Thus, the transfer function of the open loop system can be obtained

$$\frac{\Delta M_{e2}}{\Delta U_{t1}} = \frac{K_2 K_3 G_e}{1 + G_3 K_6 G_e} = \frac{K_2 \frac{K_3}{1+T'_{d0}K_3 S} \frac{K_A}{1+T_E S}}{1 + \frac{K_3 K_6 K_A}{\left(1+K_3 T'_{d0}S\right)1+T_E S}} . \tag{16}$$

Simplify the process

$$\frac{\Delta M_{e2}}{\Delta U_{t1}} = \frac{K_2/K_6}{1 + \frac{T'_{d0}}{K_6 K_A}S} . \tag{17}$$

This can be seen that fast response excitation system produces a $0° \sim 90°$ phase lag angle in the process of system oscillation, the transfer function is equivalent to an inertial link. The coordinate graphs are shown in Fig. 4.

As can be seen from the Fig. 4, the additional torque ΔM_{e2} in the ΔW axis
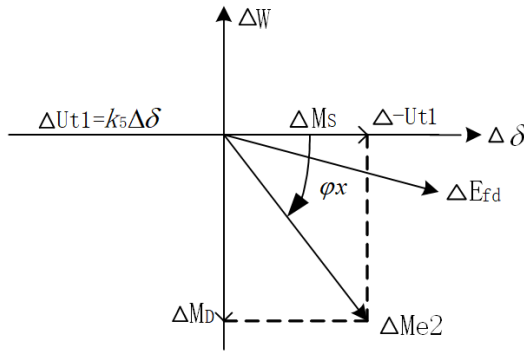
Fig. 4. Coordinate vector diagram

component is negative, produce a negative damping torque; the $\Delta\delta$ axis component is positive, produce a positive synchronous torque. The additional torque increase the generator synchronous torque, but also produce negative damping torque in the process of oscillation, the system will lose stability when the negative damping torque is greater than the inherent damping torque; The low frequency oscillation is more serious when the time constant of the fast-response excitation system is small and the voltage amplification factor is high.

3. The principle of pss suppression low frequency oscillation

Power system stabilizer as additional auxiliary part of generator excitation system, generator damping torque by adjusting the excitation input is suppressing the low frequency oscillation of system improve the small signal stability and dynamic stability is the most simple and effective way.

If the additional amount generated by the voltage regulator of the fast-response excitation system ahead of oscillation phase for the rotor angle can lead to positive damping [7] and restrain the low frequency oscillation. However, in the same phase or the reverse phase of the oscillation phase for the rotor angle, it will only lead to the oscillation phase amplitude for the rotor angle increase or decrease.

As can be seen from the Fig. 5, if a pure positive damping torque ΔM_{p} can be produced, the synthetic torque ΔM_{e} of the additional torque generated by voltage regulator ΔM_{e2} and ΔM_{p} are located in the first quadrant, the two components of the synchronous torque and damping torque are positive. The method can generate positive damping torque ΔM_{p} by inputting an additional signal ΔU_{s} at the reference point of the voltage regulator, because the input point of ΔU_{s} is the same as the reference point of the voltage regulator, so it is necessary to let the phase of ΔU_{s} advance the φ_{p} of ΔW axis meet $\varphi_{\mathrm{p}} = \varphi_{\mathrm{x}}$ to produce pure positive damping torque, This additional signal after the regulator and the hysteresis characteristics of the excitation system, can only produce the necessary damping.

Assume the transfer function of the power system stabilizer is $E_{\mathrm{p}}(s)$, according to
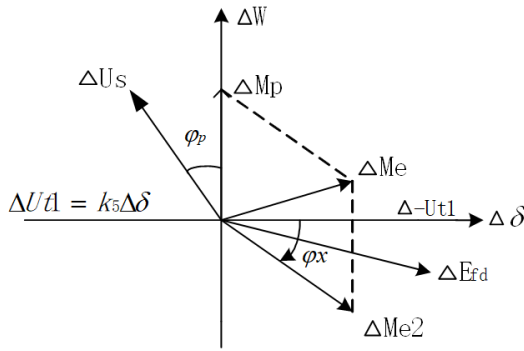
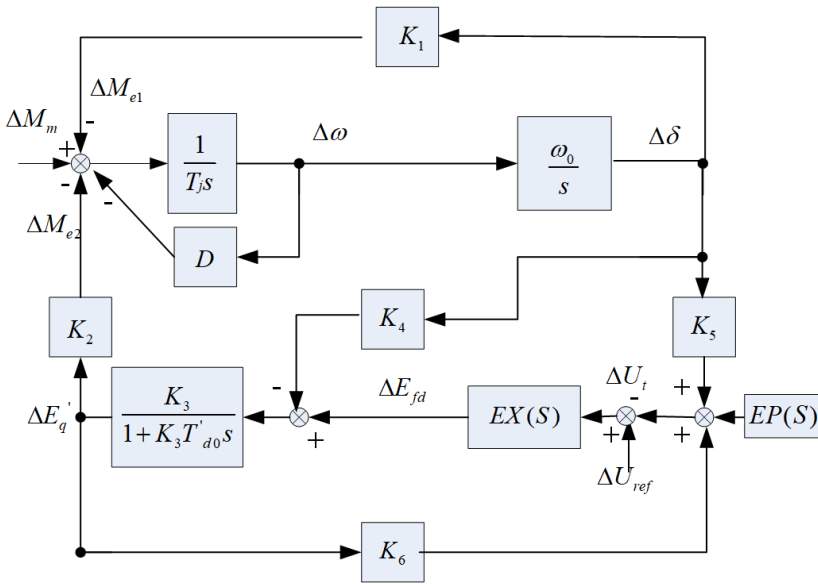Fig. 5. Damping torque vector diagram

Fig. 6. Heffron–Philips model of one machine-infinity Bus with PSS

the model shown in Fig. 6, then the electromagnetic torque is the following expression

$$\Delta M_{\mathrm{ep}} = \frac{-K_2 K_3 E_{\mathrm{x}}\left(s\right)}{1 + K_3 K_6 E_{\mathrm{x}}\left(s\right) + S K_3 T'_{\mathrm{d}0}} E_{\mathrm{p}}\left(S\right) \cdot \Delta P_{\mathrm{e}}. \tag{18}$$

So the basic principle of PSS is to deal with the additional control signal (software or hardware) to produce a phase φ_{p} of the input signal.

4. PSS model

4.1. PSS of single input signal (PSS1A)

PSS is widely used as a control device to suppress low frequency oscillation, the earliest proposed is the generator shaft speed the generator power and the voltage of the generator in frequency as the signal of the single input PSS (PSS1A) [8]. The PSS with generator power as input signal is most widely used (the block diagram is shown in Fig. 7).
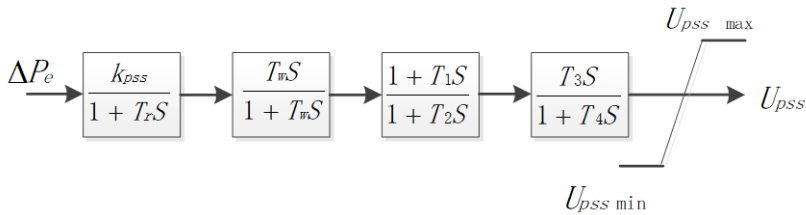

Fig. 7. Block diagram of model using generator as input signal

But the PSS with generator power as input signal can not correctly identify the power fluctuation from the engine power or the power of the system when the generator adjusting the mechanical power, lead to "reactive power reverse adjust" (as Fig. 8).
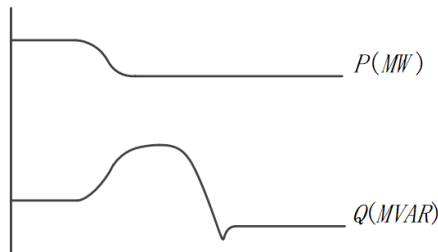

Fig. 8. PSS reverse regulationl using generator as input signal

Due to the fact that the shaft speed of the generator is difficult to measure, the torsion vibration of shafting is easy to occur, the PSS with generator shaft speed as input signal is rarely used.

The PSS with voltage of the generator in frequency as the signal requires a larger lead compensation, combined application with other input signal. It has been used in small power stations, because of its advantages such as good stability simple parameter setting and very easy to detect.

4.2. Rotational speed PSS (PSS2A/2B)

In order to solve the reverse regulation of the PSS1A model, researchers have proposed a new type of PSS, coordinate and optimize the parameters under multi operating mode of the system. In this model, the generator shaft speed and the generator power are used as input signals, compounded the acceleration integral model (PSS2A/2B, the block diagram is shown in Fig. 9).
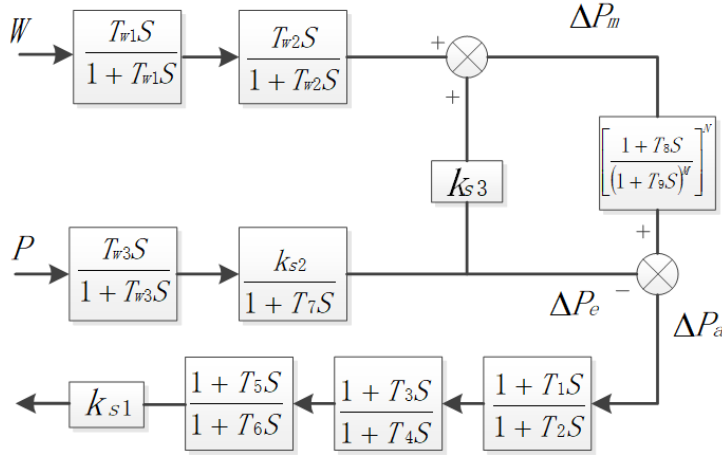

Fig. 9. Block diagram of rotational speed PSS

The driver power will change with the mechanical power when the generator regulates the mechanical power, at this point, the integral signal of PSS2A/2B model is very small, PSS does not act. The integral signal of the PSS2A/2B model is equivalent to the negative generator power integral signal, because the change of mechanical power is very small, when the system disturbance causes the generator power to change. The sum of the phase frequency characteristic and the uncompensated frequency characteristic of PSS are closed to -90 degrees by setting the parameters of the three lead lag links, provide positive damping, thereby restrain the low frequency oscillation, but also solve the reverse regulation of the PSS1A model [9].

4.3. New PSS4b model

At present, the PSS2A/2B model of acceleration integration can meet the requirements of national network, restrain the low frequency oscillation in the $0.1 - 2.5\,\mathrm{Hz}$ range. The future development of power grid are prone to ultra-low frequency oscillation less than $0.1\,\mathrm{Hz}$ with the application of UHV and the expansion of the scale for "West Power to East", The PSS2A/2B model has limited effect on the ultra-low frequency oscillation less than $0.1\,\mathrm{Hz}$.

A new PSS model named PSS4B is proposed by Canadian researchers in order to restrain the ultra-low frequency oscillation less than $0.1\,\mathrm{Hz}$. The PSS4B model

sets up three frequency bands of low frequency, intermediate frequency and high frequency, its main characteristic is to set the gain, the output limit, the phase compensation parameter in the three frequency bands, for different frequency bands to provide the appropriate positive damping [10]–[13], used to make up for it disadvantages that only use the compromise parameters to reduce the effect of low frequency oscillation because low frequency and high frequency band is hard to balance. The phase of PSS4B model can be closed to zero in the ultra-low frequency range (the previous PSS model has a large phase lead in the ultra-low frequency range, which limits the range of positive damping), while the gain and the shaft torsion oscillation can be reduced in the high frequency range [14]–[15].
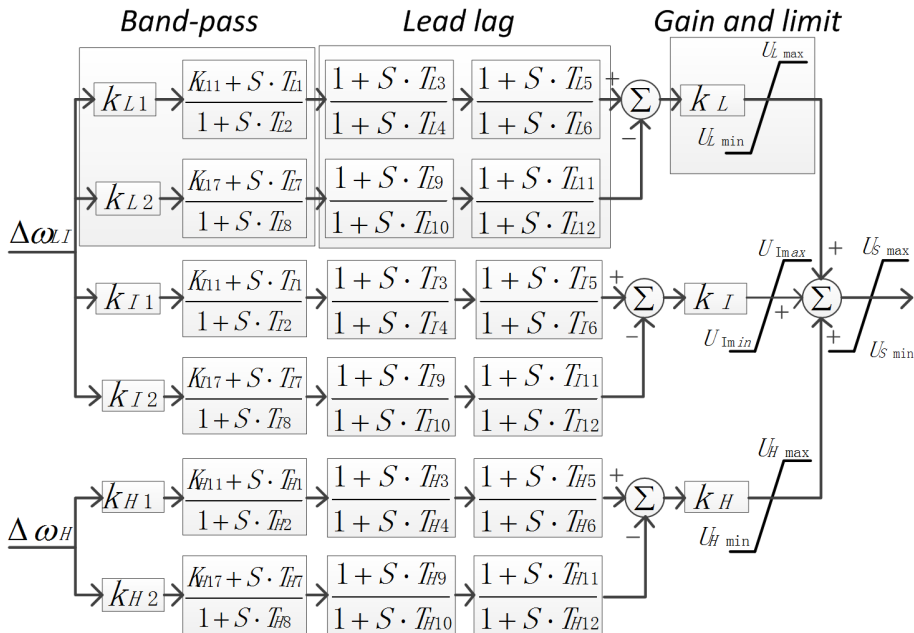

Fig. 10. Main transfer function block diagram for PSS4B

In the block diagram of the PSS4B model shown in Fig. 10, we can see that it is made up of band-pass link, lead lag link, gain and limit link.

The band-pass links of low frequency, intermediate frequency and high frequency are divided into two channels which has different central frequency values. According to the frequency range of low frequency oscillation, determine the center frequency of the three frequency band , thus determine the parameters of band-pass link (F_L for low frequency, F_I for intermediate frequency, F_H for high frequency). Take $F_L = 0.1\,\text{Hz}$, $F_I = 0.5\,\text{Hz}$, $F_H = 3\,\text{Hz}$ as an example, the frequency characteristic of the band-pass links are shown in Fig. 11.

The lead lag link is generally two stages of series connection, determine the phase compensation parameters of the three frequency bands, under the premise of
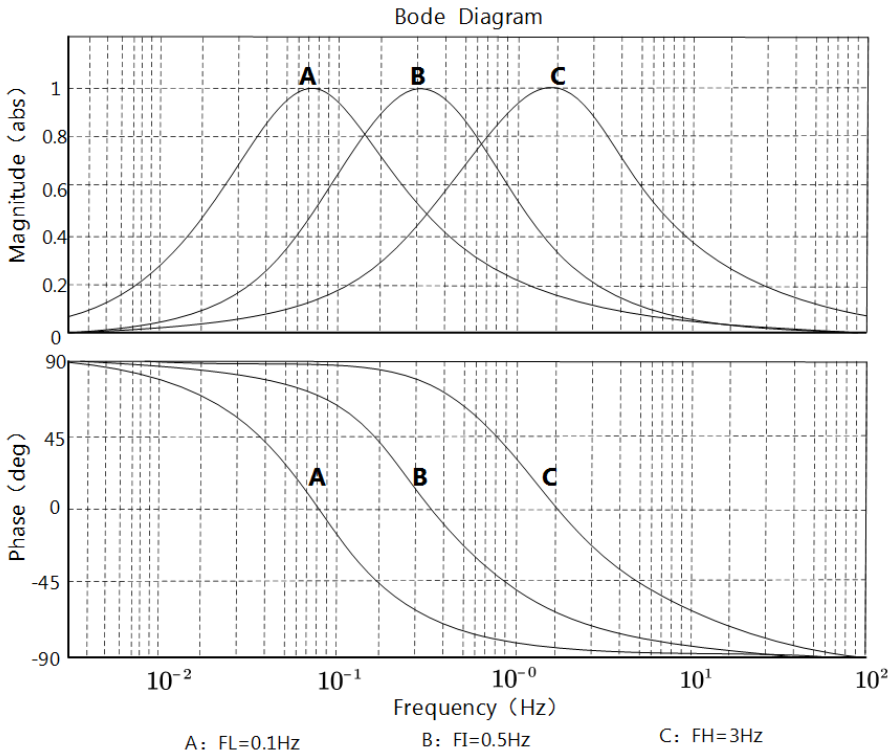
Fig. 11. Bode diagram of each link of the center frequency of 0.1, 0.5, 3 Hz

determining the phase lag characteristics of the excitation system.

5. Conclusion

Based on the mechanism of low frequency oscillation, it is very important to study the parameters of each link and the models of power system stabilizer. With the problem of low frequency oscillation is becoming more and more serious and the development of power network structure. The following conclusions are drawn in this paper:

1. The reason of the low frequency oscillation is that the time constant of the fast response excitation system is reduced, the gain is increased lead to the damping of the system is reduced and negative damping occurs.

2. The power system stabilizer is a main method to suppress the low frequency oscillation by adjusting the excitation input to generate damping in the additional control link.

3. The PSS4B model set phase compensation, gain limiting parameters with low

frequency, intermediate frequency, high frequency, provide appropriate damping in different frequency band, become a new type of power system stabilizer of the future power grid development.

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