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Abstract: The relationship between the equivalent damping factor in motion equation and the electromagnetic torque of generator has been found in this paper by analyzing the motion equation of the generator. The transformation factor from excitation electromotive force to electromagnetic torque is defined. The indirect relation between the excitation electromotive force and the equivalent damping factor is established. Based on this, the supplementary excitation control signal is proposed by means of utilizing the deviation of the angular speed as an auxiliary signal, in which the dynamic damping is directly injected into the motion equation of the generator. Finally, the operation and simulation system of the hydro turbine generating sets is established and used for simulating two operation conditions, namely line fault and low frequency oscillation. Simulation results show that the proposed method can realize the purpose of injecting damping. The study reveals that there exist a relationship between the gain coefficient in additional input branch and the additional damping coefficient.

1. Introductions

In classical third order model of the generator, the equivalent damping coefficient D is used to approximate the effect of d and q winding transient and other factors [1]. So the calculation of the equivalent damping coefficient D becomes one of the core problem in the study of the generator stability and power system. A formula was proposed to calculate the equivalent damping coefficient of the generator [2]. However, the damping characteristics of the generator will be changed when the generator connects with other equipment, whose effect is equivalent to increase of an additional damping in the original generator model [3-8]. This makes it more difficult to calculate the damping coefficient. For linear system, a method was proposed to calculate the moment coefficient based on linearization transform function [9]. In this method, the torque component of the in-phase with ω was defined as the damping torque, and thus, the damping coefficient was indirectly obtained. This calculation method of the moment coefficient is widely applied to linear system [10-12].

The main purpose of the calculation of the damping characteristics is to improve the design of the oscillation characteristics of the generator and power system. As the damping characteristics is closely related to the object system, the control and design theories based on the oscillation mode calculation of the object system have been widely used in the power system with the most success in Power System Stabilizer (PSS) [13] and Supplementary Excitation Damping Controller (SEDC) [14]. With the development of the control theory, the improvement of PSS algorithm [15,16] and its collaborative design of the multi-controllers [17-20], study of the SEDC algorithms [21,22] and its collaborative design of the multi-controllers [23,24] have been rapidly developed and many achievements are obtained.

Starting from the damping coefficient, this study proposes a method to directly inject the damping into the generator, which is not depend on the calculation of the oscillation mode, and can change the effect of equivalent damping It can be simply realized, Less parameter setting. At last the simulation of the designed system is carried out to study the self-stability and parameters characteristic.

This study is an actively exploration for the control mechanism of supplementary damping control of generator, and is the embodiment of the active control thoughts in the dynamic system.

2. Damping injection method

The traditional model of the second order single generator in differential equation form is as following:

$$\dot{\delta}_1 = \omega_B \omega_1 \tag{1}$$

$$\dot{\omega}_1 = \frac{1}{T_j} m_t - \frac{1}{T_j} m_g - \frac{1}{T_j} D \omega_1 \tag{2}$$

where $x_1 = \delta$ is the rotor (rad), $\omega_1 = \omega - 1$, ω is the angular speed (pu), $\omega_B = 314$(rad/s) is the base value of angular speed, D is the damping coefficient, T_j is the inertia time constant (s),

assume that there exist an additional damping in the generator system, Equation (2) can then be written as following:

$$\dot{\omega}_1 = \frac{1}{T_j} m_t - \frac{1}{T_j} m_g - \frac{1}{T_j}(D + D_{add})\omega_1 \tag{3}$$

Assume that the additional electromagnetic torque can be produced by the additional control input, and denoted as $m_{g\text{-add}}$, then equation (2) can be written as following:

$$\dot{\omega}_1 = \frac{1}{T_j} m_t - \frac{1}{T_j}(m_g + m_{g-add}) - \frac{1}{T_j} D \omega_1 \tag{4}$$

where $m_{g\text{-add}} = D_{add}\omega_1$, m_t is the turbine torque (pu), m_g is the torque of generator (pu).

Under grid-connected operation, the active power of the generator in per unit is approximately equal to the electromagnetic torque in per unit, that is $p_e \approx m_g$. The active power of the generator p_e is determined by the excitation electromotive force E_f, state variable δ and E_q'. Therefore, there is a relationship between p_e and E_f, which can be express as:

$$E_{f-add} = E_k(\boldsymbol{x})\omega_1 \tag{5}$$

$E_{f\text{-add}}$ is defined as additional excitation.

Notes, $E_k(\boldsymbol{x})$ is a dynamic factor, it is changing in the transient.

3. Additional control

As the $E_{f\text{-add}}$ has the feature of excitation of generator , and it is an additional control signals for the generator system, it can be introduced at the input port of the excitation system. Figure 1 shows a connection for additional control with excitation system containing a classical parallel PID.
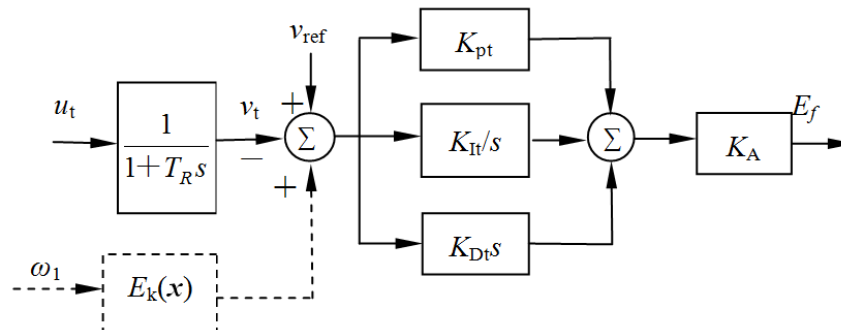
Figure 1. Schematic diagram of additional control.

Figure 1, u_t is the terminal voltage of generator (pu), v_t is the output voltage of measurement circuit of the terminal voltage (pu), v_{ref} is the reference voltage (pu), K_{Pt}, K_{It} and K_{Dt} are the proportion, integral and differential constant of the excitation PID respectively. K_A is the magnification times of the excitation regulator, E_f is the excitation electromotive force.

Figure 1 shows that if the gain E_K of the deviation signal ω_1 is too large, E_f will rapidly reach its limitation value due to the regulation action of the PID controller. Therefore, the dynamics damping provided by this kind of additional input is limited.

4. Simulation

4.1. Simulation system structure

In order to better simulate the actual operation case, the relative complete operation system of the hydro turbine generating units is used, as shown in figure 2. In figure 2, f_g and f_c are the frequency of the generator and the network in per unit respectively, K_P, K_I and K_D are respectively the proportion, integral and differential constant of PID control of the governor, b_p is the regulation scope of the governor, p_c and p_e are the given active power and measured value of the generator active power in per unit respectively.
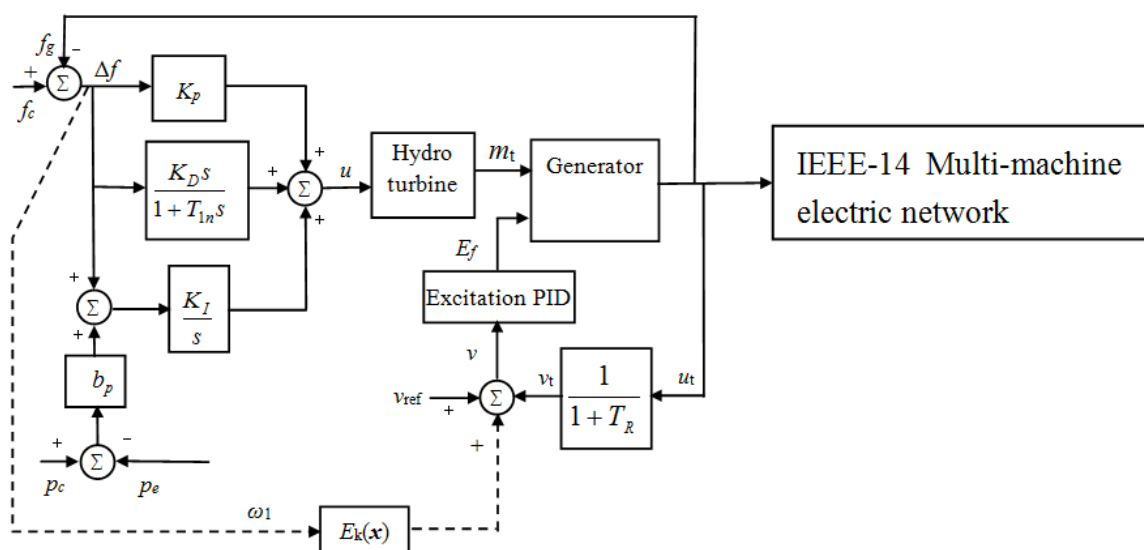

Figure 2. Simulation operation system of the hydro turbine generating sets.

The hydro turbine and the hydraulic system is the differential equations model for a single penstock and single machine with elastic water hammer. The generator and network is the third order differential equation model with a single machine infinite bus. The governor is the classical parallel correction PID controller with structure parameters being K_P=5.0, K_D=2.5, K_I=1.5, b_P=0.04. The excitation system uses the structure given by figure 1, with the structure parameter being K_{Pt}=10.0, K_{It}=5.0, K_{Dt}=0.001. The connected power system is the standard multi-machine network of IEEE-14 bus .

Based on the simulation operation system figure 2, the simulation is made under low frequency oscillation. The generator parameters are T_j=8.999 (s),T_{d0}'=5.4 (s), D=5.0.

Notes：(1) Considering controller of excitation and governor use the PLC (Programmable Logic Controller) to realize, controller execution cycles should be taken into consideration in simulation. In this article, the execution cycle of the governor control is T_t=40 (ms), execution cycles of excitation control is T_e=20 (ms), and simulation time step is 1 (ms). Excitation controller generate once output while iterative computation is carried out twenty times. Governor controller generate once output while iterative computation is carried out forty times. Other computing time controller output maintain unchanged.

(2) Refer to the structure in figure 1, the position type algorithm of excitation PID controller is following:

$$E_f(n) = E_f(n-1) + K_P[v(n) - v(n-1)]$$
$$+ K_I T_e v(n) + K_D[v(n) - 2v(n-1) + (n-2)]/T_e \qquad (6)$$

where $v(n)$, $v(n\text{-}1)$ and $v(n\text{-}2)$ is output of voltage summation element at moment n, n-1, n-2 in per unit respectively.

In equation (6), discretzation time is the execution cycle of excitation controller T_e. As such, discretization time is the execution cycle of governor controller T_t.

Based on above-mentioned operation simulation system, simulation research is conducted under low frequency oscillation.

4.2. Low frequency oscillation

(1) Oscillation signals for simulation

During low frequency oscilation, the rotor angle of generator in anytime can be decomposed into steady state rotor angle δ_0 and additional rotor angle generated by oscillation. Assume that rotor angle oscillation is the persistent oscillation, then rotor angle can be described as follow:

$$\delta = \delta_0 + \delta_D \sin \omega_D t \qquad (7)$$

where δ_0 is the rotor angle at steady state (rad), δ_D and ω_D is the peak value (rad) and angular frequency (rad/s) of rotor angle oscillation.

Assume that differential equation of steady rotor angle δ_0 remain unchanged, that is:

$$\frac{\mathrm{d}\delta_0}{\mathrm{d}t} = \omega_B(\omega - 1) \qquad (8)$$

Under low frequency persistent oscillation, the rotor angle of generator motion equation can be written as follow:

$$\frac{\mathrm{d}\delta}{\mathrm{d}t} = \omega_B(\omega - 1) + \delta_D \omega_D \cos \omega_D t \qquad (9)$$

(2) Effect of E_k on the generator active power under multi-machine

Initial operation point is p_e=0.9 (pu) and Q_e=0.3 (pu). It is assumed that the low frequency oscillation occurs at t=0 (s), disappear at t=15s, its angular frequency oscillation is ω_D=6.28 (rad s^{-1}), is

near to 1.0 (Hz), and peak of rotor angle oscillation is δ_D=0.01 (rad). Let E_k=0, and E_k=13 respectively. Active power oscillation is shown as figure 3.

It is seen from figure 3 that the active power oscillation has short period transition at the beginning of oscillation and then evolves into the sinusoidal oscillation whose frequency is equal to that of the input signal. This is consistent with the system dynamic theory. Figure 3 also shows that when additional control is added, the active power oscillation amplitude is significantly reduced. amplitude with E_k=0 is larger than that with E_k=10. That is, the oscillation amplitude of the active power decreases with the increase of the gain. Further simulation shows that there exists an upper limit for such additional damping injected. If the gain coefficient E_k is larger than 50, the oscillation amplitude at the beginning becomes larger, which may result in instability of the system. From figure 3, it is also seen when the low frequency oscillation signal disappears, the oscillation with additional control decays faster.
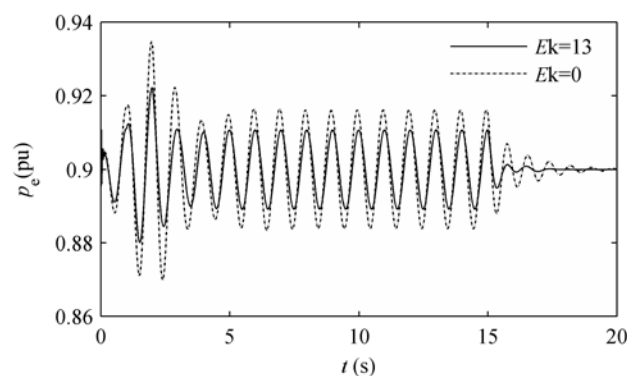

Figure 3. Simulated low frequency oscillation of the active power.

(2) Simulated comparison of additional damping injection and PSS

In figure 4, the solid line is the active power curve with the additional damping injection method. The dash-dot line is with PSS. It can be seen from the figure that at the same simulation condition, the additional damping injection has smaller oscillation amplitude than PSS. It means that the additional damping injection has the better effect.
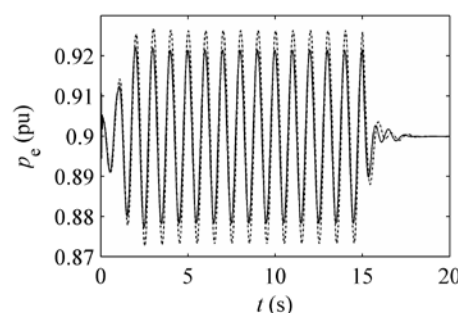

Figure 4. Simulated Active power with additional damping injection and PSS.

Figure 5 is different from figure 4. Figure 5 shows the respond of both control methods of additional damping injection and PSS under different frequency. It can be seen that within the scope of 0.1-1.0 (Hz), the effect of additional damping injection is better than that of PSS, but within the scope of 1.0-1.6 (Hz), the effect of PSS is better. we can regard it as the supplementary effect.
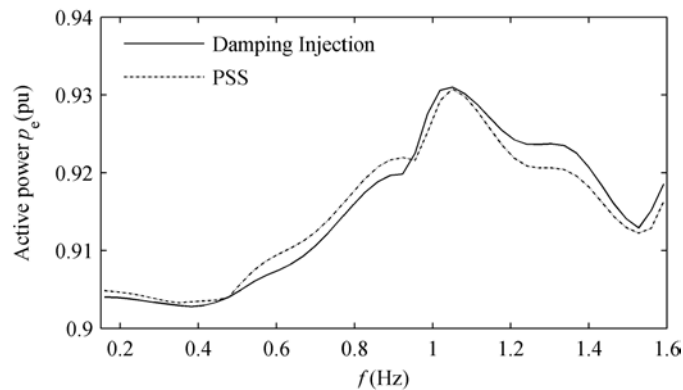
Figure 5. Comparison of active power and PSS with different f.

5. Conclusions

This paper verified the method of the additional damping injection under multi-machine system. Three conclusions can be drawn from this study:

(1) The simulation results show that the method of additional damping injection is not only fit for the multi-machine, but also effective. E_k has a great influence on the active power in the transient process. As a simple way, it provides an additional control method to increasing the damping of generator under the multi-machine.

(2) Under the multi-machine system, with the given condition, generally, the effects of the additional damping injection is better than PSS. So it might be an supplementary for PSS under the multi-machine system.

(3) In this paper the method of additional damping injection applied to a generator set is researched with simulation. It provides a basis for further study on the method applied to multiple generator set and the coordination control.

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