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Investigation of direct injection method of generator dynamic damping

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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 problems 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. Model evolution

The traditional model of the third order single generator in differential equation form is as following [1]:

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

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

$$\dot{E}'_q = -\frac{\omega_B}{T'_{d0}} \frac{X_{d\Sigma}}{X'_{d\Sigma}} E'_q \frac{\omega_B}{T'_{d0}} \frac{X_{d\Sigma} - X'_{d\Sigma}}{X'_{d\Sigma}} U_s \cos\delta + \frac{\omega_B}{T'_{d0}} E_f \tag{3}$$

where $x_1=\delta$ is the rotor (rad), $x_2=\omega_1=1-\omega$, ω *is* the angular speed (pu), $x_3=E_q'$ is the q-axis transient electromotive force (pu), ω_B=314(rad/s) is the base value of angular speed, m_t is the turbine torque value (pu), m_g is the electromagnetic torque of generator (pu), D is the damping coefficient, T_j is the inertia time constant (s), T_{d0}' is d-axis open-circuit transient time constant (s), U_s is infinite system voltage (pu), $X_{d\Sigma}$(pu) is the steady-state reactance of generator, $X_{d\Sigma}'$ (pu)is the transient reactance of generator, E_f is the excitation voltage (pu).

Our purpose is to increase the system damping through the control design. To this end, assume that there exist an additional damping in the generator system, equation(2) can then be written as following:

$$\dot{x}_2 = \frac{1}{T_j} m_t - \frac{1}{T_j} m_g - \frac{1}{T_j} (D + D_{add})\omega_1 \tag{4}$$

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:

$$\dot{x}_2 = \frac{1}{T_j} m_t - \frac{1}{T_j} (m_g + m_{g-add}) - \frac{1}{T_j} D\omega_1 \tag{5}$$

Comparing equation (4) and equation (5) reveals that the additional damping $D_{add}\omega_1$ is equivalent to the additional electromagnetic torque $m_{g\text{-}add}$ in mathematics. Therefore, the possible approach to increase additional damping of the generator system is to increase the additional electromagnetic torque of the generator. In fact, almost all additional control signals added into the system, such as the PSS signal, are introduced at the input port of the excitation system. Above analysis provides the dynamics explanation of the introduction method of the additional control in electromagnetic class.

3. Realization of additional control

Under grid-connected operation, the angular speed of the generator in per unit is ω=1. 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 exists some relation between E_f and m_g. Now, this relevance characteristic will be discussed.
Under the steady operation, combining the third order model of the generator equation (1), equation (2) and equation (3) with the expression of both the active and reactive power yields:

$$0=-\frac{\omega_B}{T'_{d0}}\frac{X_{d\Sigma}}{X'_{d\Sigma}}E'_q+\frac{\omega_B}{T'_{d0}}\frac{X_{d\Sigma}-X'_{d\Sigma}}{X'_{d\Sigma}}U_s\cos\delta+\frac{\omega_B}{T'_{d0}}E_f \tag{6}$$

$$p_{e*}=\frac{U_s\sin\delta}{X'_{d\Sigma}}E'_q+\frac{1}{2}U_s^2\sin2\delta(\frac{1}{X_{q\Sigma}}-\frac{1}{X'_{d\Sigma}}) \tag{7}$$

$$Q_{e*}=\frac{U_s\cos\delta}{X'_{d\Sigma}}E'_q-\frac{1}{2}U_s^2(\frac{1}{X_{q\Sigma}}+\frac{1}{X'_{d\Sigma}})+\frac{1}{2}U_s^2\cos2\delta(\frac{1}{X_{q\Sigma}}-\frac{1}{X'_{d\Sigma}}) \tag{8}$$

Equations (6) -(8) are used to solve for three variables δ, E'_q and E_f. Theoretically, a unique solution can be obtained. By using the relation between the δ and E'_q, there exists a certain relation between E_f and m_g under the steady operation. In transient process, such relation dynamically changes with the change of the variables δ and E'_q, Therefore, it is feasible to describe the relation between E_f and m_g by using the state transfer factor. Here, state transfer factor is complex relationships between E_f and m_g, it is related to the state of generator.
Assume that this relation can be described by means of a factor $K(\boldsymbol{x})$, which is called as the state transfer factor, then the state transfer relation can be expressed as $K(\boldsymbol{x})m_g = E_f$. Furthermore, assume that the additional electromagnetic torque $m_{g\text{-add}}$ be generated at the input port of the excitation voltage, then comparing equation(4) and equation(5) yields the approximation of the input of additional excitation $E_{f\text{-add}}$:

$$E_{f-\text{add}}=K(\boldsymbol{x})m_{g-\text{add}}=K(\boldsymbol{x})D_{\text{add}}\omega_1=E_k(\boldsymbol{x})\omega_1 \tag{9}$$

where $E_k(\boldsymbol{x})=D_{\text{add}}K(\boldsymbol{x})$. Equation (9) demonstrates that the input of additional excitation $E_{f\text{-add}}$ is directly related with the deviation of the angular speed. Therefore, additional input control needs to introduce the deviation of the angular speed as additional input signal. In addition, the method proposed is related to the exciting electromotive force E_f, so let it connect with exciting system as figure 1. For demonstration, figure 1 shows a connection for additional control with excitation system containing a classical parallel PID.

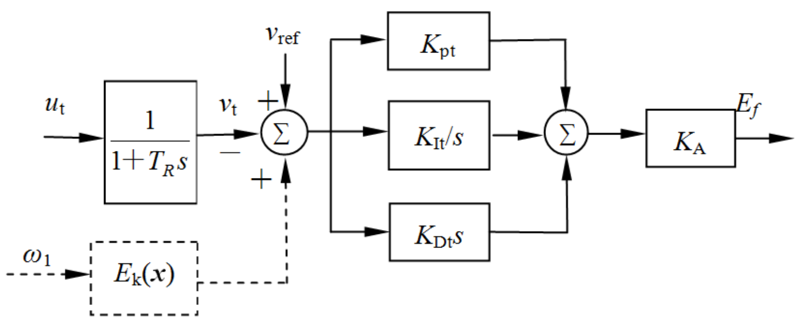

Figure 1. Schematic diagram of additional control

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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.

Analysis of the evolution of the additional control generates following discussions:

(1) In transient process, the transfer factor $K(\boldsymbol{x})$ is changeable. Therefore, E_k varies with the variation of $K(\boldsymbol{x})$, which increases the uncertainty of additional control $E_{f\text{-add}}$.

(2) Analysis of $E_k(\boldsymbol{x})$, we can find that in transient process $E_k(\boldsymbol{x})$ is also variable, and it is unable to separate D_{add} from $K(\boldsymbol{x})$. If the $D_{add}K(\boldsymbol{x})$ keeps as constant, namely, D_{add} synchronizes with the $K(\boldsymbol{x})$, in physics it is equivalent to providing additional dynamic damping, that is the damping coefficient is changed.

(3) 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.

It is worth of noting that such additional control is somehow subjective and its theoretical foundation remains to be further investigated. This study focuses only on using simulation method to examine whether the expected design purpose can be achieved.

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.

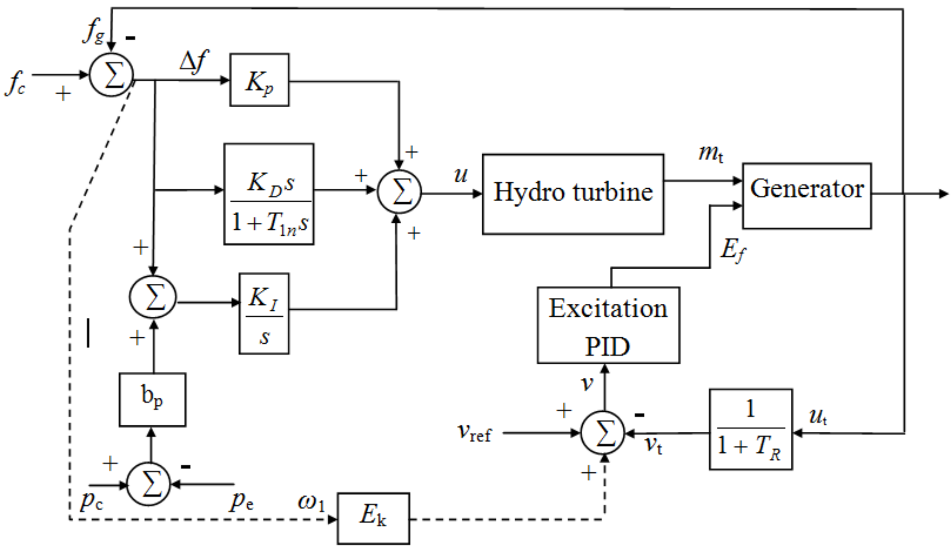

Figure 2. Simulation operation system of the hydro turbine generating sets.

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, namely the model described by equation (1)-equation (3). 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.

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

4.2. Fault disturbance

Considering the single-machine infinite bus system as shown in figure 3. The initial equilibrium is p_e=0.9(pu) and Q_e=0.3(pu). Assume that a three-phase fault be occurred at point F at t=1s, and the fault be cleared by isolating the fault circuit at t=1.1s. The fault point is simulated with an equivalent reactance X_L=2.0 (pu).

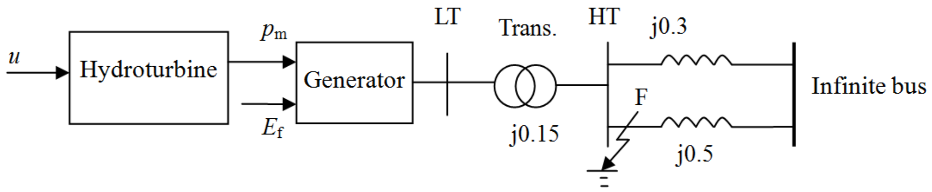

Figure 3. signal machine infinite bus system

4.2.1. Effect of E_k on the generator active power. In figure 4, different E_k is given, such as E_k=10, 20, The simulation results under the same condition are showed in figure 4. It is seen that E_k has a great influence on the active power in the transient process, and the oscillation amplitude of the active power decreases with the increase of the gain Ek while the oscillation damping is also faster for larger gain Ek. This demonstrates that increasing damping method proposed in this study is successful. Further simulation shows that if the gain coefficient Ek is larger than 50, although the oscillation damping is much faster, the oscillation amplitude at the beginning becomes larger, which may result in instability of the system. Therefore, there exists an upper limit for such additional damping injected.

*4.2.2. Dynamic change of K(**x**).* Since there are PID element and the changeable state transfer coefficient K(**x**) from the input signal ω_1 to additional damping item D_{add} as well as the object system being nonlinear, it is difficult to obtain the explicit expression between E_k and D_{add}. Therefore, simulation method is employed to analyze the relation between E_k, K(**x**) and D_{add}.

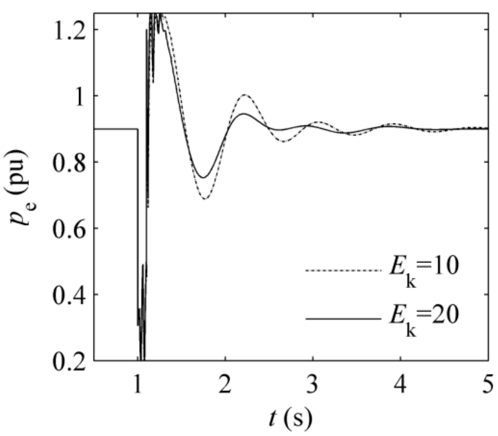

Figure 4. Variation of K(x) in the dynamic process

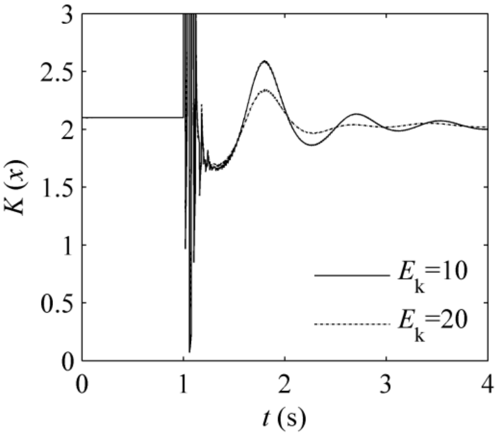

Figure 5. simulated oscillation amplitude of the active power with E_k

According to the definition of $K(\boldsymbol{x})$, that is $K(\boldsymbol{x})m_g = E_f$, $K(\boldsymbol{x})$ is the state transfer factor from E_f to m_g , so $K(\boldsymbol{x})$ can be calculated by the formula $K(\boldsymbol{x})=E_f /p_e$. In transient state $K(\boldsymbol{x})$ is changing, In the steady state $K(\boldsymbol{x})$ is constant, satisfied formula $E_k(\boldsymbol{x})=D_{add}K(\boldsymbol{x})$ proposed in section 3. If keep the change rate of D_{add} same as the $K(\boldsymbol{x})$, $E_k(\boldsymbol{x})$ can be regard as gain coefficient, so D_{add} can be regard as equivalent dynamic damping coefficient. Based on the concept of dynamic damping, additional input control can be simplified as $E_k\omega_{1.}$ The Variation of $K(\boldsymbol{x})$ in the dynamic process shows in figure 5.

4.3. Low frequency oscillation

The following states are used to simulate the influence of the additional damping control on low frequency oscillation.

The initial operation conditions are: p_e=0.9(pu) and Q_e=0.3(pu). Assume that the persistent low frequency oscillation occurs at t=1.0s, its angular frequency oscillation is ω_D=6.28(rad), which is equivalent to 1 Hz, and the peak of the rotor angle oscillation is 0.01(rad). The low frequency oscillation then disappears at t=20s (see figure 6). Giving the gain coefficient of additional control E_k=10, the active power oscillation is shown in figure 6.

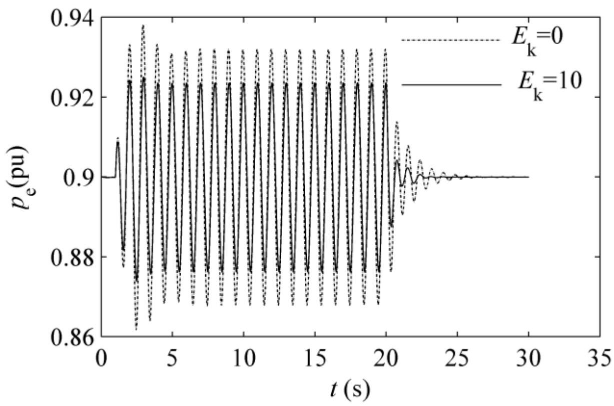

Figure 6. Simulated low frequency oscillation of the active power

It is seen from figure 6 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 6 also shows that when additional control is added; the active power oscillation amplitude is significantly reduced. When the low frequency oscillation signal disappears, the oscillation with additional control decays faster.

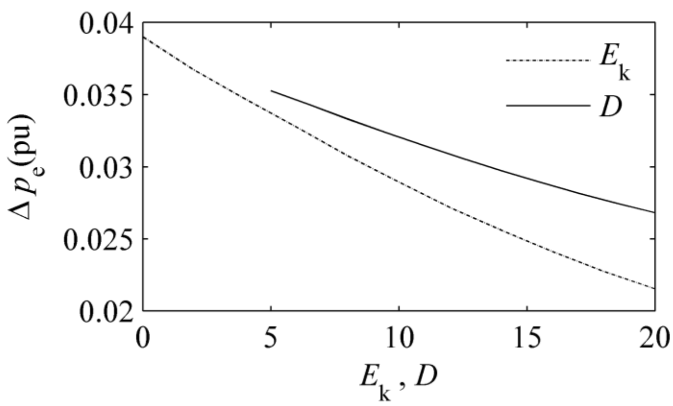

Figure7. Variation of the simulated oscillation amplitude of the active power with damping

The simulated amplitude of the active power oscillation in figure 7 shows that the supplementary control E_k and additional damping coefficient D have equivalent effect. Although E_k can not completely represent the additional damping coefficient D, there does exist a direct relation between two parameters. This relationship provides a more intuitive and more convenient approach for damping design of the generator. This is an important finding from this study.

5. Conclusions

This paper proposes a direct injection method of additional damping based on the analysis of the mechanisms of the formation of additional damping. The simulation results show that the proposed method does provide additional damping. The method is feasible, simple and intuitive. Three conclusions can be drawn from this study:

- Damping injection method proposed in this paper is an initiative damping injection method and does not depend on the object properties. Thus, compared to the methods that rely on the oscillation modes calculation, the method is simple and common to use. It solves the design failure or damping weakening issues caused by the change of the oscillation modes of the object system in PSS and SEDC design.
- This study investigates for the additional damping of the generator and its control realization. As a demonstration, simulation is only performed for two transient operations.
- It is worth of noting that for application of this method to practical excitation system, further work is required to provide solid theoretical foundations.

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References

[1] Ni Y X, Chen S T and Zhang B L 2002 Theroy and Analysis for Dynamic Power System(Beijing:Tsinghua University Press) p 46.
[2] Han Y D, Wang Z H, Chen H J. 1997 Power System Optimum Dispersion and Coordination Control. (Beijing: Tsinghua University Press) p 65.
[3] Yu Y N.1983 Dynamic Power System (Beijing: China Water Resources and Electric Power Press) p 65.
[4] Shaltout A A, Abu Al-Feilat K A.1992 IEEE Transactions on Power Systems. 7 280.
[5] Wang H F and Swift F J. Electrical. 1996 Power and Energy System.18 307.
[6] Milanovic J V. 2002 IEE Proceedings: Generation, Transmission and Distribution. 149 753.
[7] Li P, Yu Y X and Jia H J 2003 Proceedings of the CSEE. 2319.
[8] Wang X, Liu X L and Cui Z H 2008 Electric Power Automation Equipment. 28 60.
[9] Demello F P and Concordir C 1969 IEEE Transactions on Power Apparatus and Systems. 88 316.
[10] P Kundur 2002 Power System Stability and Control（Beijing: China Electric Power Press） p508.
[11] Liu X L, Liu Z and Lou H G 2006 Electric Power Automation Equipment. 26 1.
[12] Zeng Y, Zhang L X and Xu T M 2012 Large Electric Machine Technology. 2 58.
[13] IEEE Std 421.5-1992. IEEE Recommended Practice for Excitation System Models for Power System Stability Studies.
[14] IEEE Subsynchronous Resonance Working Group. 1980 IEEE Trans. on Power Apparatus and Systems. 99 1910.
[15] Liu Z Q, Gao L and Zhao X 2015 Proceedings of the CSEE. 35 1875.
[16] Ma J, Wang H J and Lo K L 2013 IET Generation, Transmission and Distribution. 7 973.
[17] Cai L J and Erlich I 2005 IEEE Transaction on Power Systems. 20 294.

IOP Conf. Series: Earth and Environmental Science **163** (2018) 012114 doi:10.1088/1755-1315/163/1/012114

[18] Shayeghi H, Safan A and Shayanfar H A 2010 Energy Conversion and Management. 51 2930.
[19] Pandi V R, Al-Hinai A and Feliachi A 2015 Energy Conversion and Management. 105 918.
[20] Tossapom S and Issarachai N 2016 IEEE Transactions on Sustainable Energy. 7 943.
[21] Xie X R, Liu H K, Han Y D 2014 IEEE Transactions on Power Systems. 29 3092.
[22] H K Liu, X R Xie and Wang L H 2015IET Gen eration, Transmission and Distribution. 9 1652.
[23] Xie X R, Wang L H and Han Y D 2016 IEEE Transactions on Power Systems. 31769.
[24] Shahgholian G and Movahedi A. 2016 IET Generation, Transmission and Distribution. 10 1860.