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The Effect of Excitation System on Synchronous Generator Transient Stability

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Abstract: The consequences of electric power outages impose studies of models that combine representations of the various components such as generators, loads, and networks in the power system. It is clear that the main role of the excitation system is supplying the field winding of the synchronous generator with the dc current for generation, as well as voltage and reactive power control to maintain a constant terminal voltage during the all loading conditions, and synchronous generator stability improvement. But addition of the excitation system with high response causes a large oscillation for the power system, because it is adding a negative damping torque. This makes a shift for the roots of motion equation from the negative part to the positive part. This paper discusses the effect of adding this type of excitation system on synchronous generator stability. A system having a synchronous generator connected to an infinity bus is discussed as case study during a sudden and continuous disturbance, and the simulation is done using MATLAB.

Keywords: Synchronous generator, stability, excitation, damping torque, oscillation.

1. INTRODUCTION

Fast excitation systems are usually acknowledged to be benefit for transient stability. But they sometimes contribute growing oscillation after the occurrence of large disturbances. The main three types of excitation systems are; systems with dc current, systems with ac current and static systems. The first type uses a dc generator, and the second type uses an ac generator as a power source for the field. The static systems consist of static parts with rectifier. This type of excitation systems which is used in a wide range now a days, have a very high response, which produces a negative damping torque.

Many studies are concerned with control, protection, response improvement of excitation systems, owing to its great important in electrical engineering especially in stability studies. [Worawut Sae-Kok, Akihiko Yokoyoma and Tanzo Nitto present excitation control system design of super-conducing generator with high response excitation in consideration of SMES effect for improving stability in multi-machine power system [1]]. [Pragy Nema discusses the use of fuzzy logic in controlling the excitation of synchronous generator [5]].[Trond Toftevaag, Emil Johansson and Astrid Petterteig show that the impedance values and excitation system tuning have an effect on synchronous generator stability [6]].

[A practical experience about dynamic performance and stability improvement of synchronous generator is presented in [4]].

2. SINGLE-MACHINE-INFINITE BUS SYSTEM

A synchronous generator connected to infinity busbar through a transmission line is considered, as in figure (1).

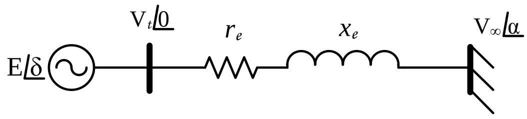

Figure (1) A synchronous generator connected to infinity bus.

Where:

E : Is the generator generated emf.
V_t: Is the generator terminal voltage. V_∞: Is the infinity bus voltage.
r_e , X_e: Are the equivalent resistance and reactance across the generator and the bus.
δ : Is the emf angle.
α: Is infinity bus voltage angle [2].

Three phase voltage of the system in fig (2) can be expressed as follows:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} v_{\infty a} \\ v_{\infty b} \\ v_{\infty c} \end{bmatrix} + r_e \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + L_e \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (2\text{-}1)$$

From Park transformation it is found that:

$$v_{odq} = P * v_{\infty abc} + r_e * P * i_{abc} + L_e * P * \frac{d}{dt} i_{abc} \quad (2\text{-}2)$$

Applying Park transformation to (2-1), the voltage equation can be expressed as follows:

$$v_d = -\sqrt{3}\, v_\infty \sin(\delta - \alpha) + r_e\, i_d + X_e\, i_q$$

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$$v_q = \sqrt{3}\, v_\infty \cos(\delta - \alpha) + r_e\, i_q - X_e\, i_d \quad (2\text{-}3)$$

3. CLASSICAL MODEL OF SYNCHRONOUS GENERATOR

The model is derived considering the following assumption [2]:-

- The effect of dampers is neglected.
- Stator resistance is neglected.
- The stator frequency is constant and equal to the synchronizing frequency.

3.1 The Simplified Model:-

The equations describing the classical model of a synchronous generator connected to infinity bus, are as follows:

$$2H \frac{d\omega}{dt} = P_m - P_e \qquad (3\text{-}1)$$

$$\Delta P_e = K_1\, \Delta\delta + K_2\, \Delta E_q^{`} \qquad (3\text{-}2)$$

$$\Delta \dot{E}_q^{`} = \frac{-1}{\tau_{d0}^{`} K_3}\, \Delta E_q^{`} - \frac{K_4}{\tau_{d0}^{`}} \Delta\delta + \frac{1}{\tau_{d0}^{`}} \Delta E_{fd} \qquad (3\text{-}3)$$

$$\Delta V_t = K_5\, \Delta\delta + K_6\; \Delta E_q^{`} \qquad (3\text{-}4)$$

Where K_6 , K_5 , K_4 , K_3 , K_2 , K_1 are
The system constants, and can be calculated using the following equations [2]:

$$K_1 = K_I\, V_\infty\, [\, E_{q0}^{\prime} [\, r_e \sin(\delta_0 - \alpha) + (X_e + X_d^{`})\, \cos(\delta_0 - \alpha + (X_q - X_d^{`})\, I_{q0}\, [(X_q + X_e)\, \sin(\delta_0 - \alpha) - r_e \cos(\delta_0 - \alpha] \qquad (3\text{-}5)$$

$$K_2 = K_I\, [\, r_e\, E_{q a_0} + I_{q0} \left(r_e^2 + (X_q + X_e)^2\right)] \qquad (3\text{-}6)$$

$$\frac{1}{K_3} = 1 + K_I (X_q + X_e)(X_d - X_d^{`}) \qquad (3\text{-}7)$$

$$K_4 = V_\infty K_I (X_d - X_d^{`})[(X_q + X_e) \sin(\delta_0 - \alpha) - re\cos\delta 0 - \alpha \qquad (3\text{-}8)$$

$$K_5 = \left[\, K_I V_\infty\, X_d^{`}\, \frac{V_{q0}}{V_{t0}} \right] [\, r_e \cos(\delta_0 - \alpha) - (X_q + Xe\ \sin\delta 0 - \alpha - \quad KIV\infty\ Xd^{`}\ Vd0Vt0Xe + Xd^{`}\cos\delta 0 - \alpha + re\ \sin\delta 0 - \alpha \qquad (3\text{-}9)$$

$$K_6 = \frac{V_{q0}}{V_{t0}} [1 - K_I\; X_d^{`}\, (X_q + X_e)] - K_I\, X_q r_e\, \frac{V_{d0}}{V_{t0}} \qquad (3\text{-}10)$$

Where:
E_{fd} : Is the stator induced voltage due to V_f, and it is given by:

$$\sqrt{3}\, E_{fd} = \frac{w_s\, KM_f}{r_f}\, V_f \qquad (3\text{-}11)$$

E_q: Is the stator induced voltage due to λ_f, and can be calculated

from;

$$\sqrt{3}\, E_q{}' = \frac{w_s\, KM_f}{L_f}\, \lambda_f \qquad (3\text{-}12)$$

4. CLASSICAL MODEL OF SYNCHRONOUS GENERATOR IN VARIABLE STATE FORM

Ii is clear that the general form of variable state equation is as follows:

$$Y = CX + DU \qquad (4\text{-}1)$$

The equations from (3-1) to (3-12) can be expressed in variable state form as follows:

$$\Delta E_q^{`} = \frac{K_3}{1 + \tau_{d0}^{`} K_3 s} (\Delta E_{fd} - K_4\, \Delta\delta)$$

$$\Delta E_q^{`} + \tau_{d0}^{`} K_3\, \Delta \dot{E}_q^{`} = K_3 \Delta E_{fd} - K_3 K_4 \Delta\delta$$

$$\Delta \dot{E}_q^{`} = \frac{-1}{\tau_{d0}^{`} K_3}\, \Delta E_q^{`} - \frac{K_4}{\tau_{d0}^{`}} \Delta\delta + \frac{1}{\tau_{d0}^{`}} \Delta E_{fd} \qquad (4\text{-}2)$$

$$\Delta w = \frac{1}{2Hs} [\, \Delta P_m - K_2\, \Delta E_q^{`} - K_1\, \Delta\delta\,]$$

$$\Delta \dot{w} = \frac{-K_2}{2H}\, \Delta E_q^{`} - \frac{K_1}{2H} \Delta\delta + \frac{1}{2H} \Delta P_m \qquad (4\text{-}3)$$

$$\Delta \dot{\delta} = w_s\, \Delta w \qquad (4\text{-}4)$$

The above equation (4-1) to (4-2) can be expressed in matrix form as follows:

$$\begin{bmatrix} \Delta \dot{E}_q^{`} \\ \Delta \dot{w} \\ \Delta \dot{\delta} \end{bmatrix} = \begin{bmatrix} \frac{-1}{\tau_{d0}^{`} K_3} & 0 & \frac{-K_4}{\tau_{d0}^{`}} \\ \frac{-K_2}{2H} & 0 & \frac{-K_1}{2H} \\ 0 & w_s & 0 \end{bmatrix} \begin{bmatrix} \Delta E_q^{`} \\ \Delta w \\ \Delta\delta \end{bmatrix} + \begin{bmatrix} \frac{1}{\tau_{d0}^{`}} & 0 \\ 0 & \frac{1}{2H} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta E_{fd} \\ \Delta P_m \end{bmatrix} \qquad (4\text{-}5)$$

5. EXCITATION SYSTEM MODEL

The block diagram of an excitation system is shown in figure (2) below [3]:

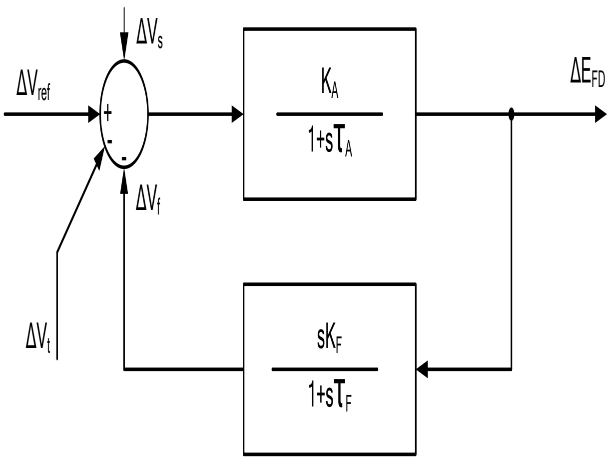

Figure (2) Excitation system block diagram

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Where:
ΔE_{fd} : Is excitation system output Voltage.
K_f : Is feedback circuit gain.
τ_f : Is the feedback circuit time constant.
K_A : Is the amplifier gain.
τ_A : Is the amplifier circuit time constant.

6. CONNECTING THE CLASSICAL MODEL WITH THE EXCITATION SYSTEM:-

Referring to figure (2) the following equations are obtained:

$$\Delta E_{fd} = \frac{K_A}{1 + S\,\tau_A}[\Delta V_{ref} - \Delta V_t - \Delta V_f]$$

$$\Delta E_{fd} + \tau_A \Delta\dot{E}_{fd} = K_A[\Delta V_{ref} - \Delta V_t - \Delta V_f] \quad (5\text{-}1)$$

$$\Delta V_t = K_5\,\Delta\delta + K_6\,\Delta E_q^{`}$$

$$\Delta\dot{E}_{fd} = \frac{1}{\tau_A}\left[-\Delta E_{fd} + K_A\,\Delta V_{ref} - K_5\,K_A\,\Delta\delta - K6\ KA\ \Delta Eq^{`} - KA\Delta Vf\right. \quad (5\text{-}2)$$

$$\frac{\Delta V_f}{\Delta E_{fd}} = \frac{S\,K_f}{1 + S\,\tau_f}$$

$$\Delta V_f + \tau_f \Delta\dot{V}_f = K_f\,\Delta\dot{E}_{fd} \quad (5\text{-}3)$$

$\Delta\dot{V}_|$

$$-K_6\,K_A\,\Delta E_q^{`} - K_A \Delta V_f)) \quad (5\text{-}4)$$

Applying (5-2) and (5-4) into (4-5) equation (5-5) is obtained:

$$\begin{bmatrix} \Delta\dot{E}_q^{`} \\ \Delta\dot{w} \\ \Delta\dot{\delta} \\ \Delta\dot{E}_{fd} \\ \Delta\dot{V}_f \end{bmatrix} = \begin{bmatrix} \frac{-1}{\tau_{d0}^{`}K_3} & 0 & \frac{-K_4}{\tau_{d0}^{`}} & \frac{1}{\tau_{d0}^{`}} & 0 \\ \frac{-K_2}{2H} & 0 & \frac{-K_1}{2H} & 0 & 0 \\ 0 & w_s & 0 & 0 & 0 \\ \frac{-K_6\,K_A}{\tau_A} & 0 & \frac{-K_5\,K_A}{\tau_A} & \frac{-1}{\tau_A} & \frac{-K_A}{\tau_A} \\ \frac{-K_6\,K_A K_f}{\tau_A\,\tau_f} & 0 & \frac{-K_5\,K_A K_f}{\tau_A \tau_f} & \frac{-K_f}{\tau_A \tau_f} & -(\frac{1}{\tau_f} + \frac{K_A K_f}{\tau_A\,\tau_f}) \end{bmatrix} \begin{bmatrix} \Delta E_q^{`} \\ \Delta w \\ \Delta\delta \\ \Delta E_{fd} \\ \Delta V_f \end{bmatrix} + \begin{bmatrix} \frac{1}{\tau_{d0}^{`}} & 0 \\ 0 & \frac{1}{2H} \\ 0 & 0 \\ \frac{K_A}{\tau_A} & 0 \\ \frac{K_A K_f}{\tau_A\,\tau_f} & 0 \end{bmatrix} \begin{bmatrix} \Delta V_{ref} \\ \Delta P_m \end{bmatrix} \quad [3]\ (5\text{-}5)$$

7. SIMULATION RESULTS

The simulation is done after subjecting the system to a small change of input mechanical power, and results are obtained using matlab SIMULINK for the case study which is a system formed of a synchronous generator connected to infinity bus through a transmission line. The study is done firstly without excitation system connected to synchronous generator, and the results are presented. After that the excitation system is added, and the results are also presented. Figures (3), (4) and (5) show the change of (ΔP_e , $\Delta\delta$, $\Delta\omega$) without excitation system. Where figures (6), (7) and (8) show the change of the same variables with time after addition of the excitation system.

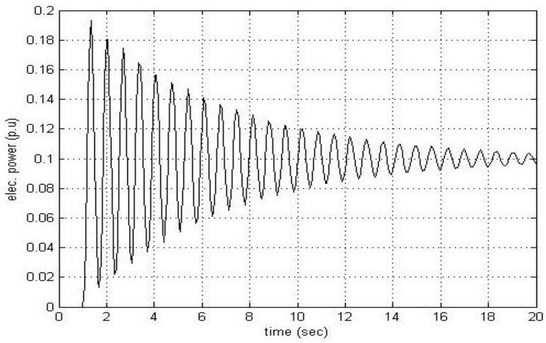

Figure (3) change of ΔP_e wit time without excitation system.

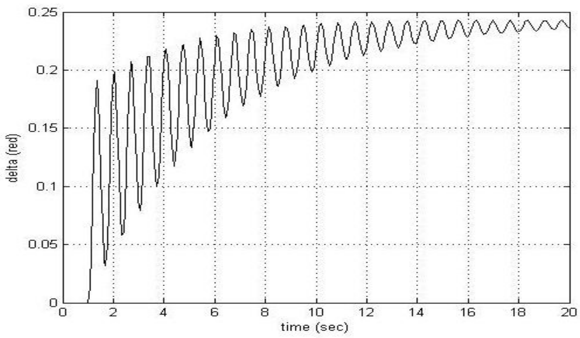

Figure (4) change of $\Delta\delta$ wit time without excitation system.

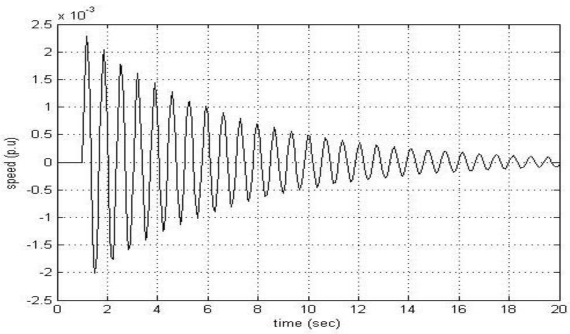

Figure (5) change of $\Delta\omega$ wit time without excitation system.

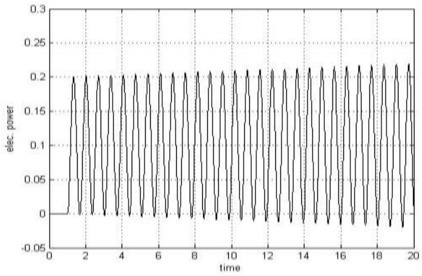

Figure (6) change of ΔP_e wit time after addition of excitation system.

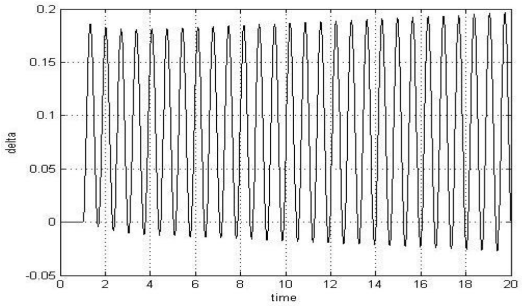

Figure (7) change of $\Delta \delta$ wit time after addition of excitation system.

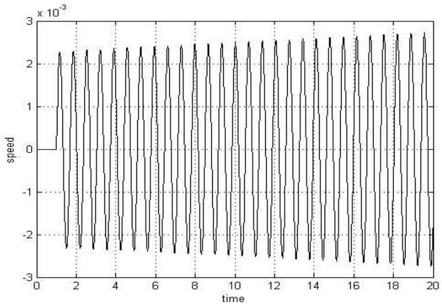

Figure (8) change of $\Delta \omega$ wit time after addition of excitation system.

8. CONCLUSION

No doubt that the excitation system play a big role in maintaining a nearly constant terminal voltage for the synchronous generator, and synchronous generator stability improvement. But this excitation system also may cause some stability troubles for the synchronous generator especially the ones with high responses. The results in figures (3), (4) and (5) show that change of electric power (ΔP_e) swing around 0.1, and then settle on it when $\Delta P_m = \Delta P_e$. Where, $\delta = \delta_0 + \Delta\delta$. The oscillation of (ΔP_e , $\Delta \delta$, $\Delta \omega$) is damped after 20 sec, and the system becomes stable again. After adding the excitation system to the same system during the disturbance, the oscillation of (ΔP_e , $\Delta \delta$, $\Delta \omega$) is increasing, and the result is loss of the stability, and this is because that excitation system added a negative damping torque due to its high response. This is clearly shown in figures (6), (7), (8),

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