Study and Simulation of No-Load Synchronous Generator Equipped with Static Excitation System

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Abstract–Synchronous machine is a two-excitation machine and is widely used in energy conversion systems such as wind energy conversion system and hydropower plants. Providing and regulating the direct current of the excitation coil of the synchronous machine is the main task of the excitation system. The excitation system in the synchronous machine must have a high voltage limit. For high reliability, each generator has its own exciter. The excitation system by controlling the excitation voltage can control the voltage and reactive transmission power and strengthen the stability of the system and cause the proper operation of a power system. In the dynamic analysis of the power system, to check the stability of the synchronous generator, it is enough to consider the excitation system and its primary drive controls can be ignored. In this article, the aim is to study and simulate the behavior of a no-load synchronous generator equipped with a static excitation system. Changes in the output voltage of the excitation system due to changes in the parameters of the excitation gain reduction (TGR) and the excitation system stabilizer (ESS) have been investigated. The simulation results show the effect of TGR and ESS on damping the oscillatory response and reducing the settling time of the response.

Keywords: Excitation system stabilizer, Energy conversion, Transient gain reduction, synchronous generator

1. Introduction

Today, the integration of renewable energy sources in power systems has become important due to the characteristics similar to synchronous machines [1,2]. Synchronous machine is one of the main parts of a power system [3,4]. Synchronous machines including synchronous generators [5,6] and synchronous motors [7,8] are widely used in energy conversion systems. Synchronous generator is used to convert mechanical energy into electrical energy.

Synchronous generator and its related controls form the most important part of an electric power system. The generator excitation system is a voltage stabilizer and reactive power controller and plays an effective role in the stability of the generator in the fault or transient state. In order to strengthen the transient stability, the excitation system must respond to the disturbance quickly, and to strengthen the stability of the small disturbance, it must apply the appropriate signal to the generator excitation.

During fluctuations in a power system, the mechanical torque changes with the opening and closing of the valves feeding the turbines. These are rapid oscillatory damping changes. In a power system, when the power demand changes suddenly, the regional frequency and the power exchange in the connecting lines are both subject to change. Changes in load demand are reflected by changes in the frequency of the power system and changes in the electrical torque of the generator output. With the balance of active power, the frequency of the system remains constant, and the imbalance of active power can directly affect the frequency and speed of the generator.

To regulated the terminal voltage and to control the frequency, synchronous generators have two automatic controllers called automatic voltage regulator (AVR) and load-frequency control (LFC). These controllers indirectly affect the active and reactive powers of the generator. Fig. 1 shows a single machine power system with control systems.

There are various means of supplying dc power to the field winding of an electric machine. Excitation systems can be divided into three groups based on the excitation power source: direct current (dc) excitation system [9], alternating current (ac) excitation system [10] and static excitation system [11,12]

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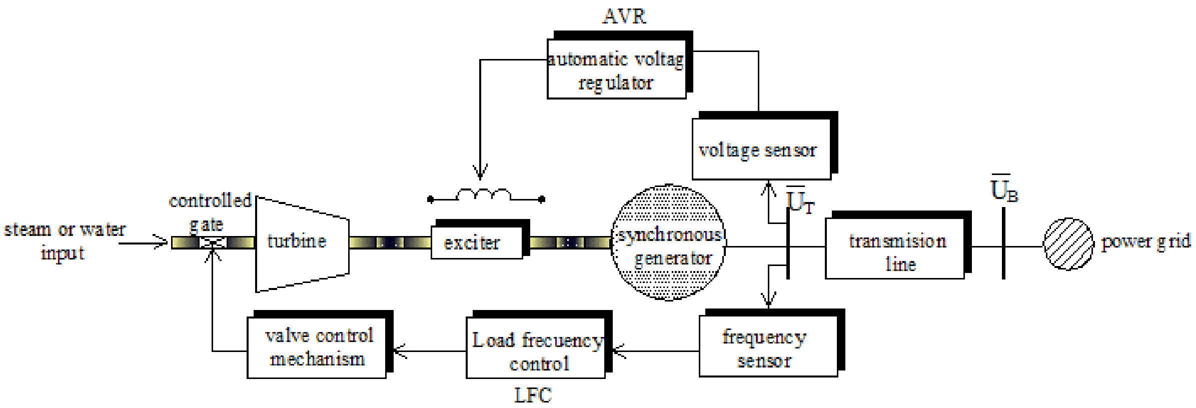


Fig. 1. Connecting the synchronous machine to the infinite bus with the display of the excitation system

Static excitation control systems do not have the power of time delay due to the development of electronic elements, and a stabilizer is not needed to ensure their stability in the no-load state of the generator [13].

Among the static excitation systems that are widely used, we can mention systems with controllable rectifier and voltage source, systems with rectifier and combined source, and excitation systems with controllable rectifier and combined source.

Among the advantages of the static method, we can mention simple repairs due to the fact that all devices are stationary, and the disadvantages include the problems of cleaning them due to the presence of coal and problems in the destruction of the collector. Among the disadvantages of the dynamic method, it can be mentioned that it is difficult to balance the generators with the turbine due to the addition of one or two generators because a longer and heavier axis is needed. Also, the response of their control commands appears later than the static method. One of their advantages compared to the static method is that they do not require coal [14,15].

In this paper, the behavior of an unloaded synchronous generator equipped with a static excitation system is studied and simulated. The equations of the system are expressed in the state space along with the block diagram of the system. The effect of reducing the transient gain and stabilizer of the excitation system on the output voltage of the excitation system is presented using simulation in MATLAB software, which shows the effect of TGR and ESS on the damping of the oscillatory response and the reduction of the settling time of the response. As can be seen, with the presence of the ESS or TGR, the oscillations have decreased. Also, the effect on peak values of voltage changes is also well shown.

2. Studied System Block Diagram

The block diagram of the no-load synchronous generator model equipped with a static excitation system is shown in fig. 2.Many advanced excitation systems can be described with static excitation system block diagram. The generator terminal voltage (U_T) is determined from the excitation voltage through the first-order block with the time constant T'_{do}. The output of the excitation system is represented by the gain K_A and the time constant T_A by U_A. The transient gain reduction block is considered with two time constants T_B and T_C and its output with U_B [16,17].

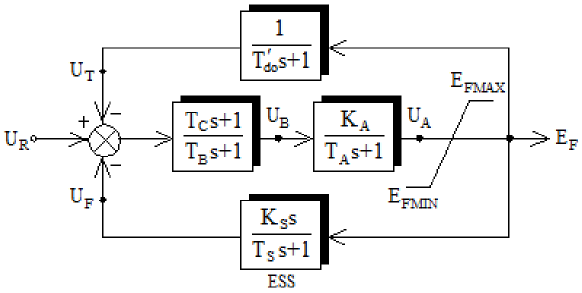


Fig. 2. Block diagram of no-load synchronous generator

To reduce the excitation, gain at high frequencies, transient gain reduction is used to reduce the negative contribution of the regulator in the system damping. It is necessary to use TGR based on the dynamic characteristics of the system and its effect on other parameters of the excitation system. The transfer function of the transient gain reduction block is determined using a pre-phase-post-phase converter and is [18,19]:

$$G_T(s)=\frac{\Delta E_F(s)}{\Delta E_T(s)}=\frac{1+T_B s}{1+T_C s} \tag{1}$$

where the time constants T_B and T_C are the transient gain and the steady state gain, respectively, and usually their values are one and ten seconds, respectively. Fig. 3 shows the frequency response of the TGR transfer function. As can be seen, the phase of the TGR transfer function at high frequencies is equal to zero, and the minimum value of the phase is about 55 degrees at the angular frequency of 0.3 radians/second.

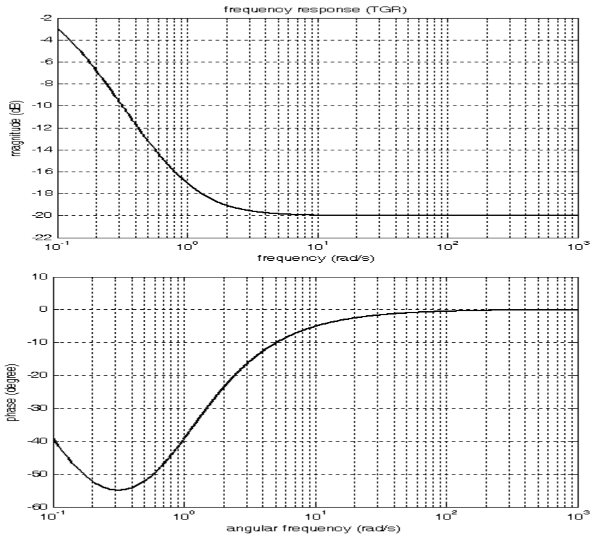


Fig. 3. Frequency response of transient gain reduction transform function

3. System Equations in State Space

By choosing the four state variables UA, U_C, U_T and U_F according to fig. 4, the system equations in the state space are:

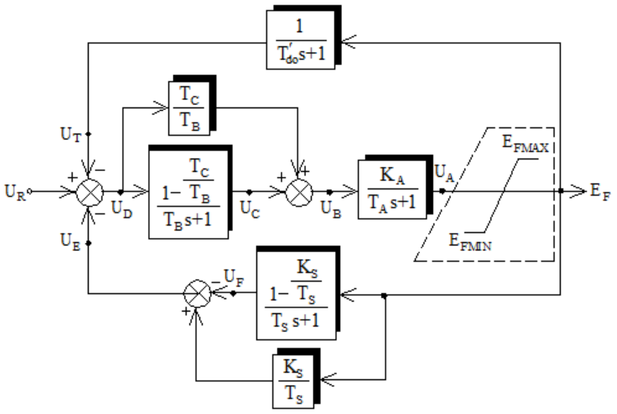


Fig. 4. Introduction of system state variables

$$\frac{d}{dt}U_A = -\frac{1}{T_A}U_A + \frac{K_A}{T_A}U_B$$

$$= -\frac{1}{T_A}U_A + \frac{K_A}{T_A}\overbrace{[U_C + \frac{T_C}{T_B}\underbrace{(U_R - U_T - U_E)}_{U_D}]}^{U_B} \qquad (2)$$

$$\frac{d}{dt}U_C = -\frac{1}{T_B}[U_C - (1-\frac{T_C}{T_B})U_D] \qquad (3)$$

$$\frac{d}{dt}U_T = -\frac{1}{T'_{do}}(U_T - E_F) \qquad (4)$$

$$\frac{d}{dt}U_F = -\frac{1}{T_F}(U_F - \frac{K_S}{T_S}E_F) \qquad (5)$$

where U_E, U_D and E_F are to:

$$U_E = -U_F + \frac{K_S}{T_S}E_F \qquad (6)$$

$$U_D = U_R - U_T - U_E \qquad (7)$$

$$E_F = \begin{cases} U_A & E_{FMIN} \le E_F \le E_{FMAX} \\ E_{FMIN} & E_F < E_{FMIN} \\ E_{FMAX} & E_{FMAX} < E_F \end{cases} \qquad (8)$$

The initial conditions for state variables are:

$$U_A(0) = E_F(0) = 1 \qquad (9)$$

$$U_F(0) = \frac{K_S}{T_S}E_F(0) = \frac{0.03}{1} = 0.03 \qquad (10)$$

The initial condition of auxiliary variable U_B is determined using the differential equation of state variable U_A:

$$U_B(0) = \frac{1}{K_A}U_A(0) \qquad (11)$$

At instant zero for U_C we have:

$$U_C(0) = (1-\frac{T_C}{T_B})U_D(0) \qquad (12)$$

As shown in the block diagram, the following relationship always exists between the variables:

$$U_C + \frac{T_C}{T_B}U_D = U_B \qquad (13)$$

Therefore, at the zero moment, the following relationship holds:

$$U_C(0) = (1-\frac{T_C}{T_B})(\frac{T_B}{T_C})[U_B(0) - U_C(0)]$$

$$\Rightarrow \frac{T_B}{T_C}U_C(0) = (\frac{T_B}{T_C} - 1)\frac{U_A(0)}{K_A}$$

$$\Rightarrow U_C(0) = (1-\frac{T_C}{T_B})\frac{U_A(0)}{K_A} \qquad (14)$$

The initial conditions of other variables are:

$$U_D(0) = \frac{1}{1-\frac{T_C}{T_B}}U_C(0)$$

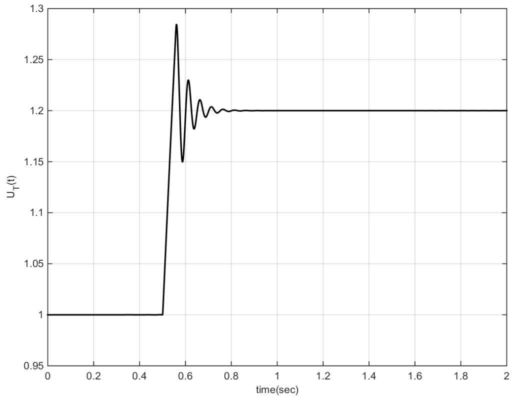
$$= (\frac{1}{1-\frac{T_C}{T_B}})(1-\frac{T_C}{T_B})\frac{U_A(0)}{K_A} = \frac{U_A(0)}{K_A} \qquad (15)$$

$$U_E(0) = \frac{K_S}{T_S}E_F(0) - U_F(0) = 0 \qquad (16)$$

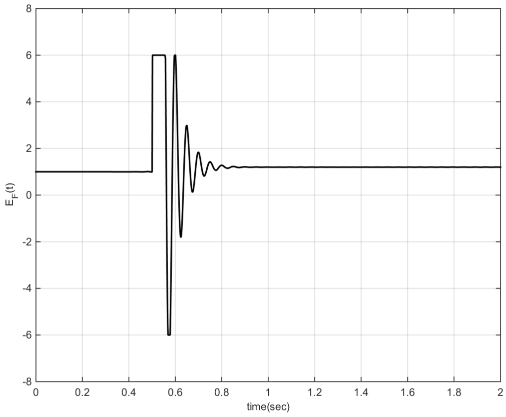
$$U_R(0) = U_D(0) + U_T(0) + U_E(0) = \frac{U_A(0)}{K_A} + U_T(0) \qquad (17)$$

4. Simulation Results and Discussion

Simulation results without considering the effect of TGR and EES in fig. 5 [in this case $U_C=U_F=0$], without considering the effect of EES and considering the effect of TGR in fig. 6 [in this case $U_F=0$], considering the EES effect and without considering the TGR effect is shown in fig. 7 [in this case $U_C=0$] and considering the EES and TGR effect is shown in fig. 8.



(a) Changes in excitation voltage (E_F)



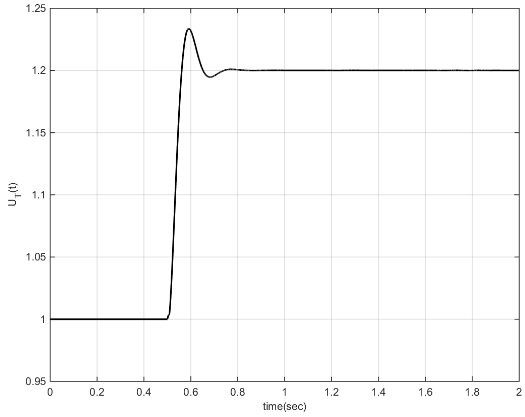
(b) Changes in terminal voltage (U_T)

Fig. 5. Simulation results without considering the effect of EES and TGR ($T_C=0$, $T_B=0$, $K_S=0$)

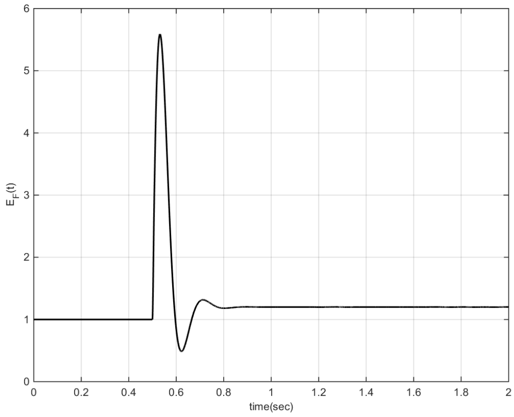
As can be seen, there is oscillation in the power system without the effect of EES and TGR, and a lot of time is needed to damp the response, so EES or TGR is needed to damp the oscillatory response. Normally, either TGR is used in the forward path or EES is used in the feedback path.

In fig. 5, the system is simulated without the effect of ESS and TGR. In other figures, the system response has been compared with this mode. The effect of the ESS and TGR is shown in other results.

The simulation results for three different values of time constant T'_{do} are shown in figs. figs. 9 and 10. As can be seen, with the increase of the time constant T'_{do}, the response fluctuations decrease. Using a ESS or TGR helps in reducing the settling time for when the $T'_{do}$is small.

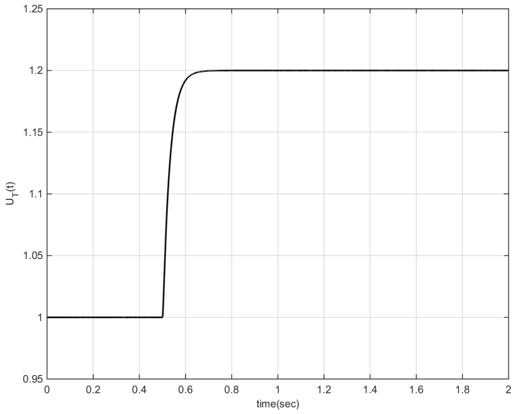


(a) Changes in excitation voltage (E_F)

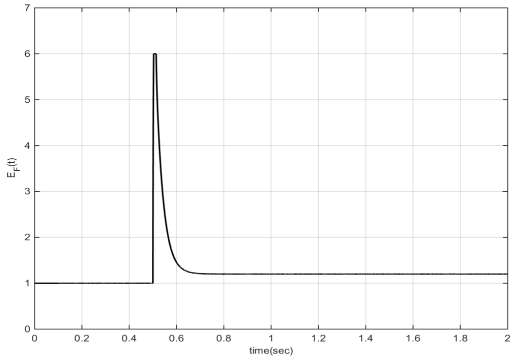


(b) Changes in terminal voltage (U_T)

Fig. 6. Simulation results with TGR and without considering the effect of EES (T_C=1s, $K_S=0$)

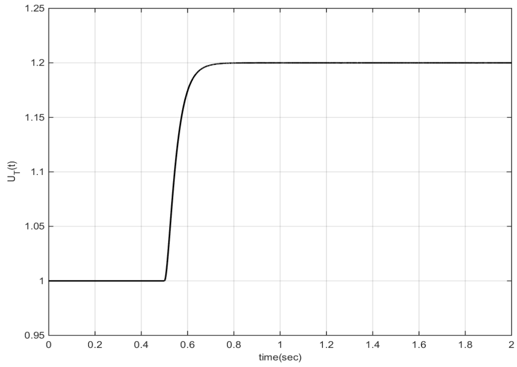


(a) Changes in excitation voltage (E_F)

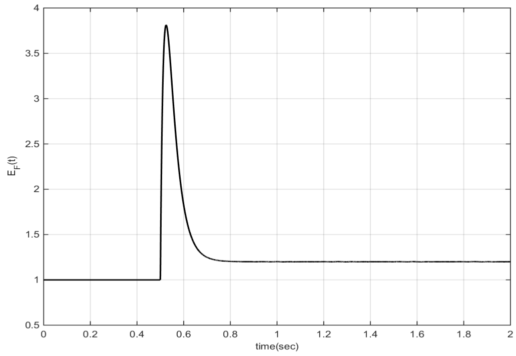


(b) Changes in terminal voltage (U_T)

Fig. 7. Simulation results with ESS and without considering the effect of TGR (T_C=0, T_B=0, K_S=0.03)



(a) Changes in excitation voltage (E_F)



(b) Changes in terminal voltage (U_T)

Fig. 8. Simulation results without considering the effect of EES and TGR (T_C=1s, K_S=0.03)

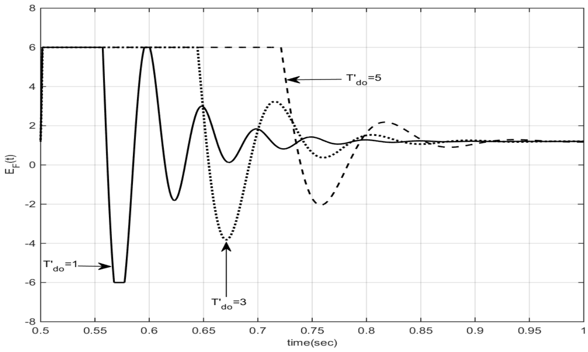


Fig. 9. The effect of time constant T'_{do} on changes of excitation voltage without considering the effect of ESS and TGR (T_C=10s, K_S=0)

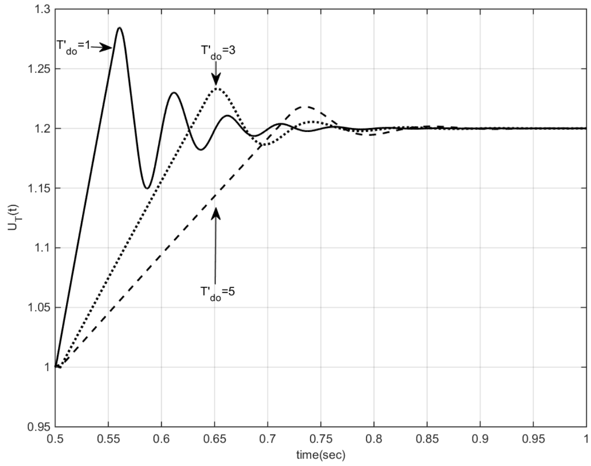


Fig. 10. The effect of time constant T'_{do} on changes of excitation voltage without considering the effect of ESS and TGR (T_C=10s, K_S=0)

5. Conclusion

The current of the synchronous machine is controlled in such a way as to change the terminal voltage of the machine. The time constant of the field circuit is high and fast field control requires a forced field.

Excitation system is considered as a system that is used to generate flux by passing current in the field coil. The main requirements of an excitation system are reliability under all service conditions, simplicity of control, ease of maintenance, stability and fast transient response. Automatic generator voltage control systems in power plants use a static excitation method to improve transient stability. In this article, the study and simulation of no-load synchronous generator equipped with static excitation system was presented. The simulation results have shown the effect of reducing the transient gain and stabilizer of the excitation system on the excitation output voltage. As stated, for damping the oscillatory response, a stabilizer of the excitation system is needed in the feedback path and the transient gain reduction in the forward path. The results show that the ESS or TGR are necessary to correct the system response, which tends to oscillate and has a long settling time. Also, there is no significant advantage in the presence of ESS and TGR simultaneously in the system. The studied system is for generator without load, which can be generalized to the system with generator with load.

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