MODELLING OF A DC EXCITATION OF A SYNCHRONOUS GENERATOR

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Abstract. This paper describes the modelling of a DC excitation system of a synchronous generator. DC excitation system is one of the various methods of excitation that are applied in power systems. Even though the AC excitation methods are commonly used nowadays, this method still has wide usage in many power system industries. A mathematical model is developed using differential equations from the first principles. Transfer functions of the developed equations are presented and implemented in Matlab Simulink. The performance of the DC excitation is analysed under steady state and transient operations.

Key Words. Synchronous Generator, DC Excitation system, Field voltage, System stability.

1. INTRODUCTION

Excitation systems are the basis of power system stability and control. The design of excitation system and its parameters play a major role in the performance of the power system control and protection [1]. Many power systems fail as a result of poor design of the excitation system. When fault occurs, it becomes very difficult to troubleshoot if the excitation was not thoroughly and clearly modelled and designed [2]. Therefore, modelling of excitation systems is very crucial and it requires thorough detail of every single part in order to allow quick fault detection. The AC excitation system is the most popular excitation method. However, magnetic field could build up and collapse with AC power, making the generated current drop to zero. In this paper the DC excitation system is modelled and analyzed in terms of its performance under steady state and transient conditions. This method of excitation is chosen over the other methods owing to its simplicity, reliability and lower design costs. It is easier to troubleshoot simple systems. The most important aspect in DC excitation systems is frequent maintenance since they use brushes and slip-rings.

2. DC EXCITATION MODEL

The complete model of the DC excitation is shown in shown by the transfer function block diagram in Fig 1.

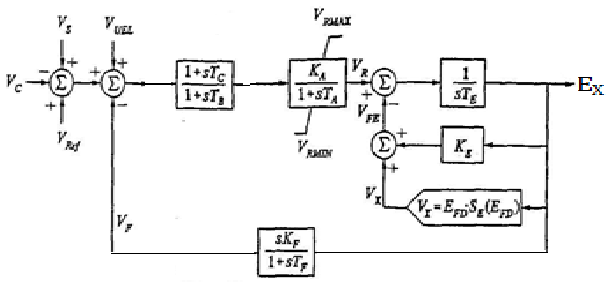

Fig. 1: DC Exciter model.

This model is as a result of the building blocks of the excitation system. The transfer function blocks were obtained from equation derivations from the first principles as in detailed in section 2.1.

2.1 Mathematical model

DC excitation system can be either separately excited or self-excited. The excitation model incorporates both separately excited and self-excited; the only difference between the two is with the parameters. When the self-excited system is used the parameters need to be set in such a way that the terminal field voltage is achieved with V_R set to zero. The exciter consists of a field winding and an armature winding. The field winding is composed of a resistor and an inductor as illustrated in Fig. 2. The field winding of the DC exciter is highly inductive; the inductor plays a significant role.

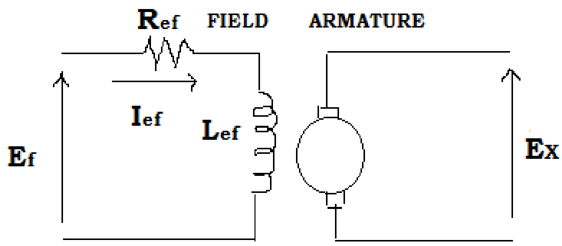

Fig. 2: Separately excited exciter circuit.

$$E_f = R_{ef}\ i_f + L_f \frac{di_f}{dt} \tag{1}$$

Where R_{ef} is the field resistance and L_f the field inductance.

The voltage equation (1) of the field is the basis of the model of a DC excitation system. This equation is applied for both the separately excited and self-excited DC exciter method. Neglecting the flux leakages, the terminal voltage of the DC exciter is proportional to the flux linkage, as shown by equation (2). The proportionality constant is "k_x".

The proportionality constant is dependent on the speed and design of the DC exciter parameters. The exciter terminal voltage is as in equation (2).

$$E_x = k_x \psi \qquad (2)$$

The flux linkage can be expressed as in (3)

$$\psi = L_f \; i_f \qquad (3)$$

$$E_f = R_{ef} \; i_f \; + \frac{d\psi}{dt} \qquad (4)$$

The load saturation curve in Fig. 3 shows the non-linear characteristics of the field current and the terminal voltage of the exciter. When the exciter is loaded, due to armature reaction, the terminal voltage of the exciter terminals drops. Therefore, when modelling the exciter the loading effect and the saturation effect have to be taken into account. The two armature reaction effects are represented by the two curves, open circuit curve and saturation curve. Tangent to the open-circuit saturation curve is the air-gap line. The slope of the air-gap line denotes the resistance of the field on the air-gap.

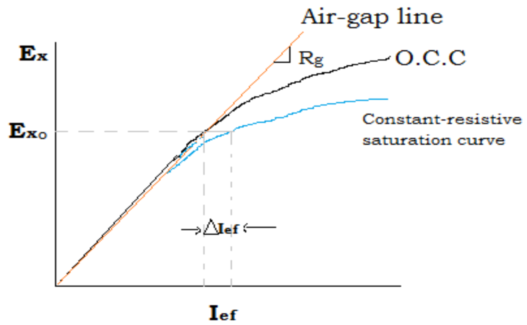

Fig. 3: Terminal voltage characteristic curves

R_g denotes the slope of the air-gap line. Therefore, the field current depends on current due to the air-gap line and the current due to the difference between the two saturation curves

$$i_f = \frac{E_x}{R_g} + \Delta i_f \qquad (5)$$

Δi_f is a non-linear function of E_x and it is expressed as in (6)

$$\Delta i_f = E_x \, S_e(E_x) \qquad (6)$$

The function S_e (E_x) is a saturation function that depends on E_x. Equation (2) is now written as in (7).

$$E_x = \frac{R_f}{R_g} E_x + R_f \;\; S_e(E_x) E_x + \frac{1}{k_x}\frac{dE_x}{dt} \qquad (7)$$

In order to obtain the required transfer functions the equation had to be represented in per unit system. Equivalent per unit quantities of the variables are given by their base quantities as expressed in equation (8).

$$\bar{E}_x = \frac{R_f}{R_g} \bar{E}_x [1 + \bar{S}_e(E_x) \; \bar{E}_x] + \frac{1}{k_x}\frac{dE_x}{dt} \qquad (8)$$

The saturation function is expressed as in (9).

$$\bar{S}_e(E_x) \bar{E}_x = \frac{\overline{\Delta i_f}}{\bar{E}_x} = R_g S_e(E_x) \qquad (9)$$

The proportionality constant k_x is derived from equation (2) and is now written as in (10).

$$k_x = \frac{E_x}{\psi} = \frac{E_x}{L_f I_f} = \frac{R_g}{L_f} \times \frac{E_x}{i_f} \qquad (10)$$

For any given values of the field current and the terminal voltage of the exciter, the quantity L_{fu} can be obtained as in (11).

$$L_{fu} = L_f \frac{\overline{I_{fo}}}{\overline{E_{xo}}} \qquad (11)$$

Therefore, the proportionality constant is denoted as in (12).

$$k_x = \frac{R_g}{L_{fu}} \qquad (12)$$

The derivation of the transfer function equation using the per-unit method yields the final equation (13).

$$\bar{E}_x = K_E \, \bar{E}_x + \bar{S}_e\left(\bar{E}_x\right) \bar{E}_x + T_E \frac{d\,\bar{E}_x}{dt} \qquad (13)$$

The model for the exciter is shown in Fig. 4.

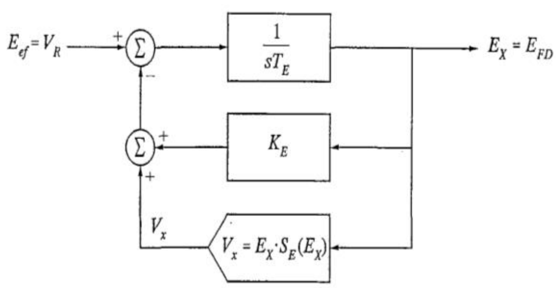

Fig. 4: Exciter Model

2 SIMULATION RESULTS

The excitation system was tested on Matlab with a plant system consisting of a 3.25MVA synchronous generator with a diesel engine Governor as its prime mover, and a 1MVA resistive load. The initial condition values of the excitation system and constant values were given as the standard IEEE values [3]. The values of the circuit parameters were measured through Simulink simulation and analysis was made under transient and steady state conditions.

2.1 Steady state

The plant was operated on both full load and no-load conditions. The terminal voltage from the synchronous generator was measured and simulated under full load condition as in Fig. 5.

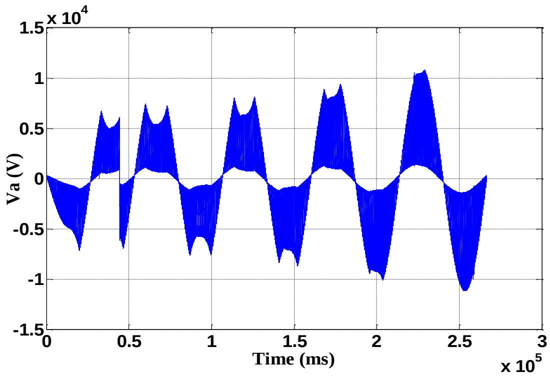

Fig. 5: Terminal voltage on full load.

The terminal voltage increased to almost twice the full load value when the load was removed. The result indicates that the load has a high resistance. Therefore, the voltage regulation was high. The terminal voltage under no-load conditions is shown in Fig. 6.

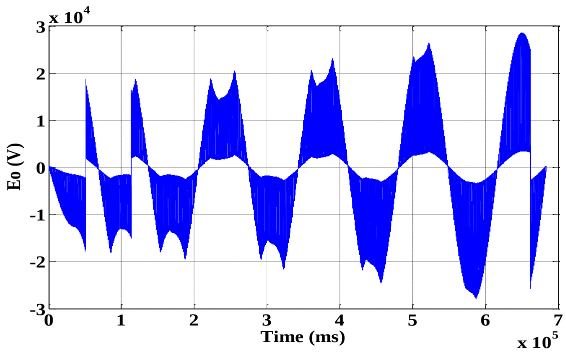

Fig. 6: No-load terminal voltage.

After the synchronous machine was excited by a field voltage, it started off by supplying a constant active power of about half the rated value as shown in Fig 7. After a few seconds the active power dropped instantaneously to a negative value and the machine started supplying an increasing reactive power, as shown in Fig. 8.

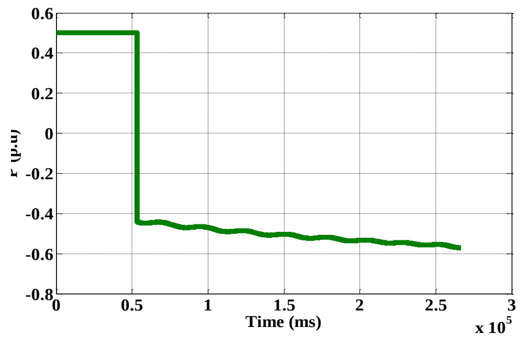

Figure 7: Per unit Active power under load conditions.

Figure 8 the per unit reactive power under load conditions. The reactive power picked up exactly the same instant the active power was dropping in Fig. 7, and the machine started delivering reactive power to the resistive load.

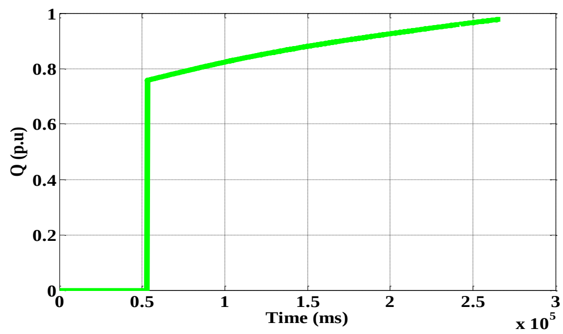

Fig. 8: Reactive power under load conditions

2.2 Transient-state conditions

The reaction of the plant system due to changes in the excitation system was tested by creating a line to ground fault in the excitation system. Observing from Fig. 9, it is observed that the magnitude of generated voltage is very small and dropped down to a very large negative number. This drop was as a result of the unbalanced voltages between the lines. The system was no longer operating under three phase conditions and the unbalanced phase was affecting the healthy phases.

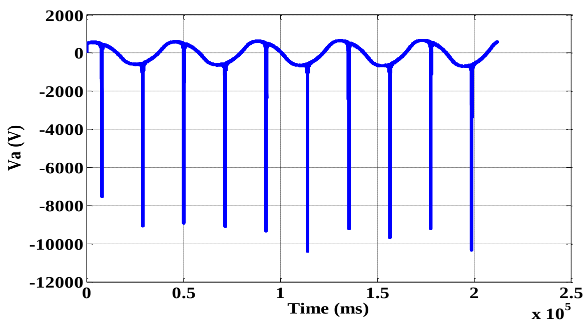

Fig. 9: Transient-state terminal voltage.

Under no-load transient state conditions the system was resisting the sudden change.

The plot in Fig. 10 shows the generated voltage reaches the same maximum amplitude that it reached under healthy conditions, the difference this time is that the voltage could only be seen for a very few milli-seconds (ms) then it drops again. It does the latter for equal interval and it never reaches a steady value. This is still due to the unbalanced voltage phases. The system is not stable enough to retain a high voltage, which is the reason the voltage drops very fast.

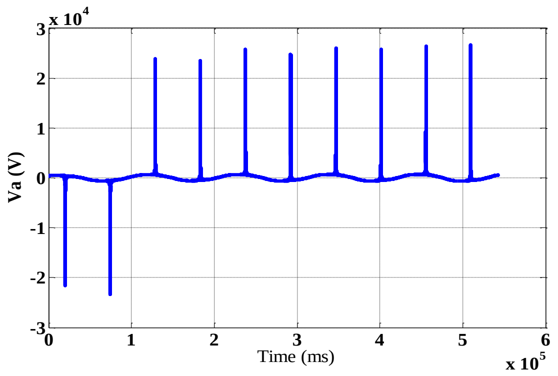

Fig. 10: Transient-state no-load terminal voltage

The system behaved differently under transient conditions as compared to normal (healthy) conditions in terms of the active power. The machine started supplying active power to the load as opposed to the steady-state conditions whereby reactive power was delivered to the load and active power was absorbed in the system.

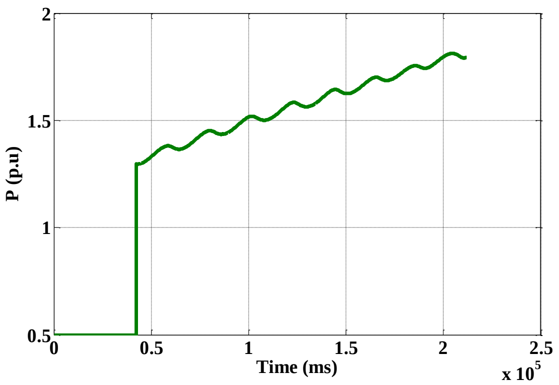

Fig. 11: Transient-state active power.

The reactive power delivered to the load remained the same during the transient state condition. Therefore, both active power and reactive power were delivered during the unhealthy conditions.

4. CONCLUSION

The paper has described and discussed how an excitation system of a synchronous generator is modelled. The results have given conclusive evidence that excitation systems are crucial components of power systems. Changes in the excitation due to faults or unstable conditions affect the whole excitation system. A DC excitation system does not only provide field power to the synchronous generator but it also monitors the system performance and stability. Any undesired behavior in the system can be corrected through the excitation system feedback. The regulator can sensor the terminal voltage, amplify and filter it to acceptable levels for excitation.

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