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Simulation Analysis of a Synchronous Generator System under Fault Conditions

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Abstract—**In this paper, simulations of a three-phase short-circuit fault that occurs on a 230 kV bus have been carried out in a stand-alone simplified power system based on Matlab/Simulink, the results confirm the validity of the excitation control system including auxiliary control links-power system stabilizer (PSS) on stability of the power system, and the effect of the PSS2A is superior than the Genetic PSS. It also presents the changes of the first amplitude of the transient field fault current and the transient armature fault current along with different phase angles when the fault happens on the armature windings. Simulation results under different fault durations indicate that the time to reach steady-state will reduce substantially if amplitude of the armature transient fault current decreases slightly. Furthermore, this paper presents the changes of maximum deviation and steady-state time of the rotor speed along with the length of fault duration. Simulations about fault happened on different locations are also carried out in this stand-alone simplified power system, it turned out that the transient stability level of the system is higher when fault happens before the transformer compared with the fault happens on the point that behind the transformer.**

Keywords-excitation; PSS; control; three-phase short circuit fault; transient armature current; transient field current; fault time; rotor speed

I. INTRODUCTION

Synchronous generators is commonly used in electric systems. The generator is supplied with real power from a prime mover usually a turbine, while the excitation current is provided by the excitation system [1]. Synchronous generator excitation control system is one of the most important parts of power system, it needs to reduce the fluctuation of the voltage, balance the distribution of inactive power, increase anti-interference and stable operation of the system [2]. Besides, low frequency oscillation in the large-scale Internet is easy to produce with the expanding of power grid, it seriously threatens the safe and stable operation of power system. Power system stabilizer (PSS) is to suppress low frequency oscillation and has been widely used as an earliest developed additional excitation controller.

The short-circuit of a synchronous generator will seriously damage the power system, although the process is extremely short (usually about 0.1 ~ 0.3 s), it is significant in analyzing of armature fault current. And the short-circuit test is one of the oldest and most familiar methods to obtain information on the transient performance of synchronous machines [3].

In Matlab, the function modules of the synchronous generator has two inputs, one is a mechanical power input, the other is a excitation voltage input, and the control of the synchronous generator is accomplished by this two inputs. The regulation of mechanical power is achieved through the control function of the speed governor while the adjustment of the excitation voltage is implemented by the excitation regulator. Owing that not considering speed adjustment, and regarding the mechanical power input as a constant in the research of power system electromagnetic transient process. Therefore, this article focuses on the excitation part. The procedure is to excite the generator which is represented in Section II, and Section III presents the excitation control principle. A three phase symmetrical short-circuit is then applied to the bus and the waveform results are recorded in Section IV. In addition, the analysis of fault impaction on the generator are described in Section V. Finally, Section VI summarizes the control effect of excitation system including auxiliary control links-PSS and the effects of faults on the system operation.

II. THE MATHEMATICAL MODEL OF SYNCHRONOUS GENERATOR

The mathematical model of a synchronous generator is the basis for qualitative analysis of a synchronous generator and its system stability, which includes the voltage equation and flux equation describing the electromagnetic characteristics, and the rotor motion equation indicating the rotor speed and torque change. Assuming that the generator and the power system work in Sync and the generator excitation is control of power system, adopting Synchronous Machine pu Standard synchronous generator model, its six order mathematical model is as follows [4]

$$T_J \frac{d\omega}{dt} = M_m - M_c - D(\omega - \omega_0) \quad (1)$$

$$\frac{d\delta}{dt} = \omega - \omega_0 \quad (2)$$

$$T_{do}^{'} \frac{dE_q^{'}}{dt} = E_{fd} - (x_d - x_d^{'}) I_d - E_q^{'} \quad (3)$$

$$T_{do}^{''}\frac{dE_q^{''}}{dt}=-E_q^{''}-(x_d^{'}-x_d^{''})I_d+E_q^{'}+T_{do}^{''}\frac{dE_q^{'}}{dt} \quad (4)$$

$$T_{qo}^{'}\frac{dE_d^{'}}{dt}=-E_d^{'}+(x_q-x_q^{'})I_q \quad (5)$$

$$T_{qo}^{''}\frac{dE_d^{''}}{dt}=-E_d^{''}-(x_q^{'}-x_q^{''})I_q+E_d^{'}+T_{qo}^{''}\frac{dE_d^{'}}{dt} \quad (6)$$

where, T_J = Generator inertia constant, M_m = Mechanical torque, M_c = electromagnetic torque, D = Damping coefficient, ω, ω_0 = rotor speed and the synchronous speed, E_{fd} = field voltage, E'_d, E'_q = d and q axis components of transient electric potential, E''_d, E''_q = d and q axis components of subtransient electric potential, x_d, x'_d, x''_d, x_q, x'_q, x''_q = d and q axis synchronous reactance, transient reactance and subtransient reactance respectively, T'_{d0}, T'_{q0} = d and q axis transient time constants, T''_{d0}, T''_{q0} = d and q axis subtransient time constants.

III. Generator Excitation System Control Theory

Excitation system is commonly composed of the excitation power unit and the excitation regulator. Meanwhile, generator and its excitation system are known as the excitation control system which is a typical feedback control system. The control principle is shown in Fig. 1. The excitation system supplies rated voltage/current excitation when the generator works at normal conditions. And the voltage detection unit will change compared with the given reference voltage when the generator terminal voltage changes due to some reason on the machine, then the formation of control signal acts on the excitation unit to change the output voltage/current [5]. In other words, the implementation of the adjustment of the excitation voltage or current can achieve the goal of automatic adjustment for generator voltage.

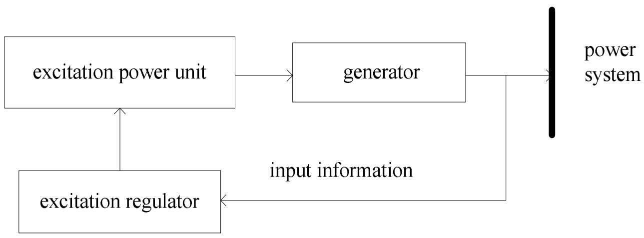

Figure 1. Block diagram of excitation control system.

Researches show that introducing additional control signal other than the power voltage, such as the electric power, rotor speed, frequency or the combination of the above signals in the generator excitation control system can add damping to the rotor oscillations of the synchronous machine and increase the stability of power system after a certain phase processing. The output signal of the PSS is used as an additional input to the excitation system block. This article firstly uses the Genetic PSS whose input is speed deviation, $d\omega$, then uses the PSS2A whose inputs are rotor speed and active power, and Fig. 2 shows a model of the PSS2A [6].

The PSS2A model consists of DC blocking links, a low pass filter, general gain, phase-compensation systems, and an output limiter. The general gain K determines the amount of damping produced by the stabilizer. The low pass filter must maintain a sufficient bandwidth, making the signal of the mechanical power reflect the change of the actual mechanical power rapidly. The phase compensation system is represented by a cascade of two first-order lead-lag transfer functions used to compensate the phase lag between the excitation voltage and the electrical torque of the synchronous machine.

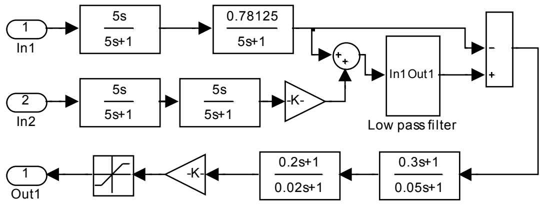

Figure 2. A model of the PSS2A.

IV. Synchronous Generator Excitation System Modeling and Simulation in Matlab

A. The System Simulation Model

A stand-alone simplified power system model is built to study the operation characteristics of a generator excitation control system. The generator system consists of the synchronous generator, excitation system and PSS. The power system is simulated by a standard transformer, transmission line, loads, the voltage source and the measuring element. As shown in Fig. 3, a three-phase generator rated 200 MVA, 13.8 kV, 112.5 rpm is connected to a 230 kV network through a Delta-Y 210 MVA transformer, the parameters of the synchronous generator and Genetic PSS are shown in Table I and Table II (pu).

TABLE I. Parameters of a Synchronous Machine

T_J	D	p	x_d	x_d’	x_d’’
3.2	0	32	1.305	0.296	0.252
x_q	x_q’’	T_{d0}’	T_{d0}’	T_{q0}’	T_{q0}’’
0.474	0.243	1.010	0.053	0	0.100

TABLE II. Parameters of the Genetic PSS

Sensor time constant	K	Wash-out time constant	T_{1n}	T_{1d}
3e-5	20	2	50e-3	20e-3
T_{2n}	T_{2d}	Vs_{max}	Vs_{min}	Initial input
3	5.4	0.15	-0.15	0

B. Fault Occurs on the 230 kV Bus

At t = 0.1 s, a three-phase short circuit fault occurs on the 230 kV bus and the fault is cleared at t = 0.2 s. The results of this simulation are shown in Fig. 4.

The simulation starts in steady state which is initialized by the Powergui. Observe that the terminal voltage V_a that plotted in Fig. 4(a) is 1.0 pu at the beginning of the simulation. It falls to about 0.4 pu during the fault. This phenomenon means that there is a demagnetization effect between the excitation electromotive force and induction electromotive force, and it leads breakdown voltage decreases. Then V_a returns to nominal quickly after the fault is cleared at t = 0.2 s. This quick response in terminal voltage is due to the fact that the limitation output V_f which is shown in Fig. 4 (b) can go as high as 10.5 pu during the fault.

The speed of the machine increases to 1.01 pu during the fault, then it oscillates around 1.00 pu no matter the PSS participate in the running or not. However, the speed of the rotor in the system without the PSS would take much more time to achieve stable state which can be seen clearly from Fig. 4(c). Meanwhile, the effect of the PSS2A is better than the Genetic PSS. Furthermore, the speed takes much time than the terminal voltage to stable situation mainly because the rate of valve opening/closing in the governor system is limited [7].

The last plot in Fig. 4(d) indicates that the field current during the fault can reach to 4.5 pu then restore to a stable state at roughly 1.0 s. On the one hand, it is known from the joule's law that resistance heat increases and the temperature of the generator rise when the field current increases. On the other hand, core will be overly saturated when the field current is too large, and part of the field lines would go through shell to composite circuits making the chassis produce heat because of eddy current, which induces the temperature of the generator rise further.

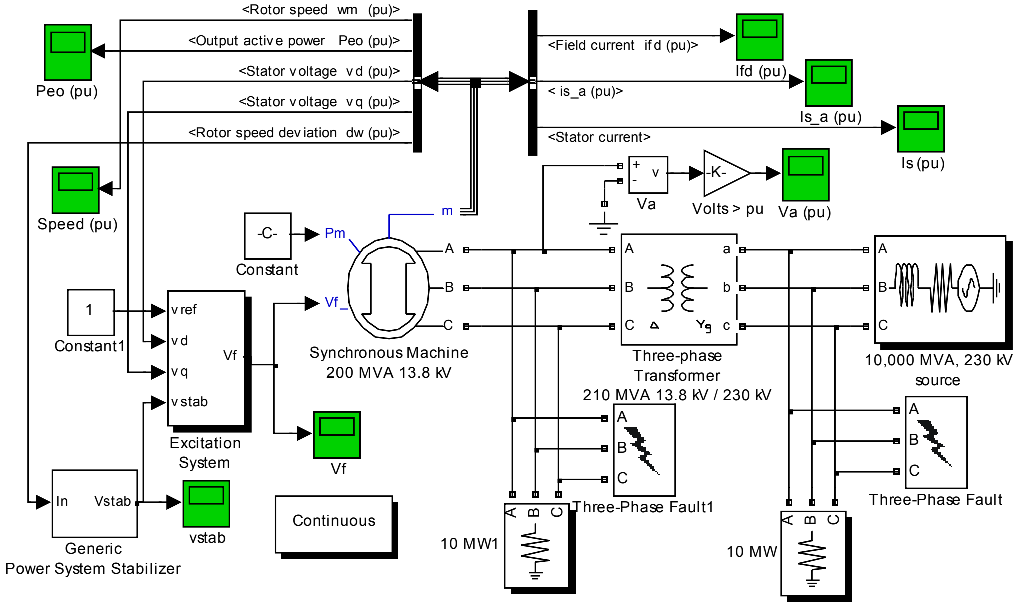

Figure 3. Model of a stand-alone simplified power system.

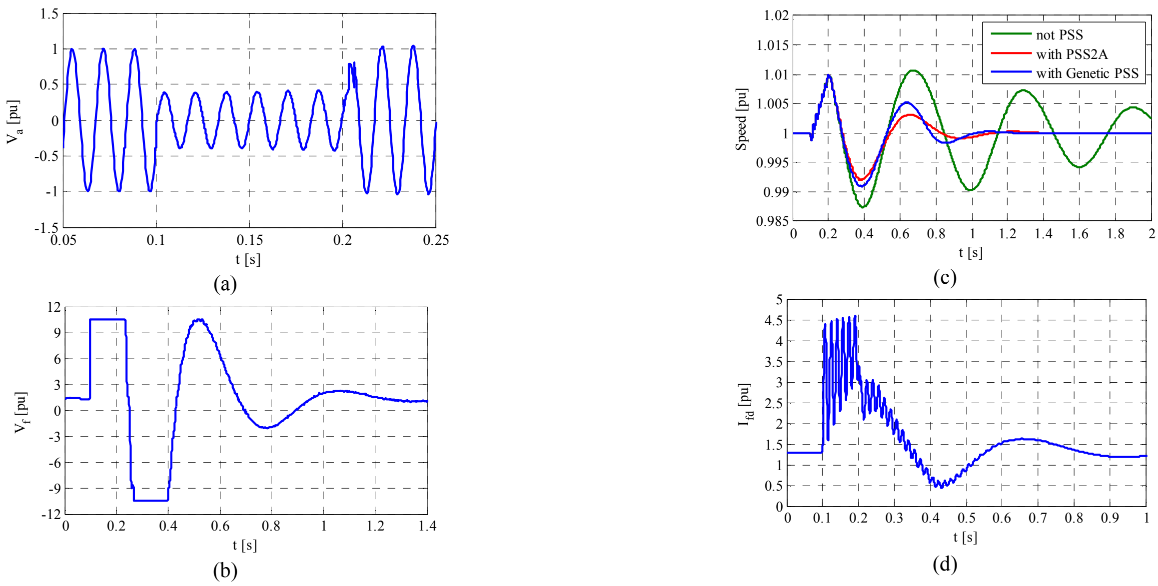

Figure 4. The results of simulation: (a) V_a; (b) V_f; (c) Speed; (d) I_{fd}.

V. THREE-PHASE SHORT-CIRCUIT FAULT ANALYSIS

A. The Influence of the Phase Angle of Fault on the Currents

Fig. 4(d) manifests that the field current will change greatly once the fault happened, thus this part presents the changes of first amplitudes of the transient field fault current and the transient armature fault current along with different phase angles when the fault happened on the armature windings. In other words, the fault happened on the 13.8 kV bus. Fig. 5 displays the changes of the first amplitudes of current in a voltage cycle under the condition of transient stability.

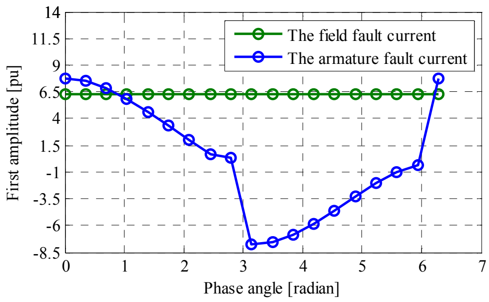

Figure 5. The changes of the first amplitude of the transient fault current along with A phase voltage phase angle.

The waveforms in the Fig. 5 indicate that the first amplitude of the field fault current almost do not change no matter which phase angle is when the fault happened on the armature windings while the first amplitude of the armature fault current change periodically, and this cycle time is nearly as same as the armature voltage cycle time, the stator three-phase current waveforms are shown in Fig. 6 during 13.8 kV bus in the short circuit fault process. Moreover, three-phase voltage in the stator before failure can be expressed as follows (pu)

$$
\begin{aligned}
u_A &= \sin(\omega t - 23.42^0) \\
u_B &= \sin(\omega t - 23.42^0 - 120^0) \\
u_C &= \sin(\omega t - 23.42^0 + 120^0)
\end{aligned} \tag{7}
$$

where, $\omega = 2\pi f$, $f = 60$ Hz.

As can be seen from Fig. 6, each phase current with a different magnitude whose changes is shown in the Fig. 5. System power do not change immediately on the moment that the fault happened while the three-phase voltage values in (7) are different, thus each phase current values are different. And the maximum transient armature fault current lies in the phase that the absolute value of armature fault voltage is minimum of the three and it reaches the maximal when the minimum voltage wave is going through zero, which can also be seen from the Fig. 5. The formulas in reference [8] also explain this phenomenon theoretically.

B. The Influence of Fault Duration on the Generator

Fig. 7 describes the different armature current waveforms with different fault durations but having same fault phase angle.

The graphs in the Fig. 7 manifest that the armature current restore to stability after 3 s when the maximum armature fault current reaches about 5.43 pu while the stable time reduce to 1 s when the maximum current approximately dropped to 4.55 pu, and the current waveforms have great improvement, this changes show that the greater the armature fault current is, the more harmful effect on the system. Therefore, it is necessary to install current limiter device in the middle of the circuit.

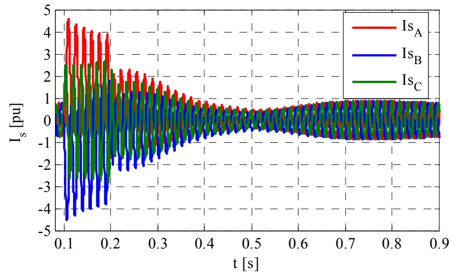

Figure 6. Three-phase current in the stator.

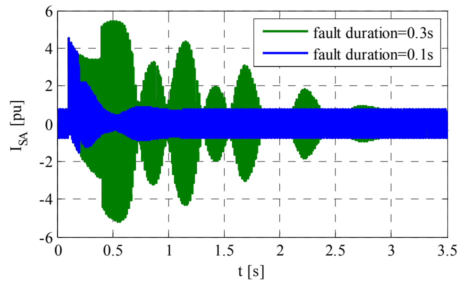

Figure 7. Phase A armature current during the fault.

Moreover, increasing/decreasing the fault duration on the basis of the above process, the changes of maximum deviation and stable time of the rotor speed are plotted in Fig. 8, these processes based on the premise of system can return to stability again.

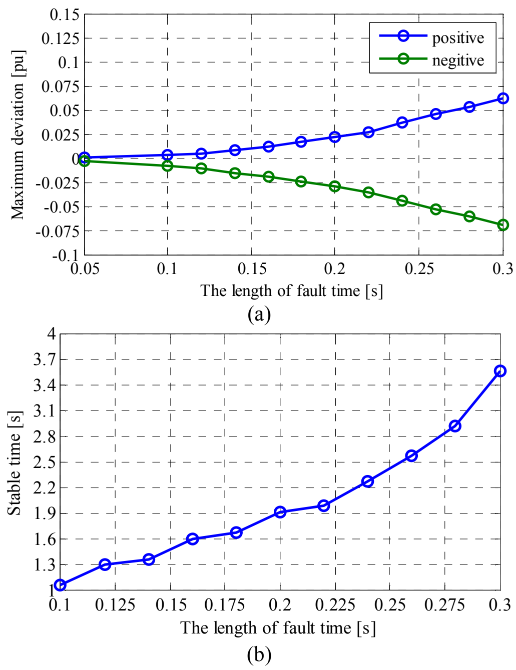

Figure 8. The changes of maximum deviation and stable time of the rotor speed: (a) The change of maximum deviation along with the length of fault duration; (b) The change of stable time along with the length of fault duration.

Fig. 8 describes the changes of maximum deviation and stable time along with the length of fault duration which indicates that the faster remove of the fault from system, the smaller effect on the system. Thus, specific measures that aim at improving transient stability include relay protection which can achieve rapid removal of the fault.

C. The Voltage Waveforms and Limit Clearing Times in Different Points

The voltage in Fig. 4(a) will change if the three-phase short-circuit fault happened on the 13.8 kV bus. The simulation waveforms when the faults occur on 13.8 kV bus and 230 kV bus are shown in Fig. 9.

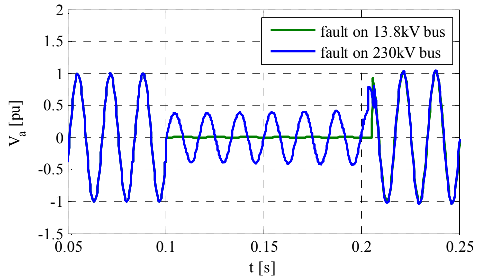

Figure 9. The waveforms of V_a in two different locations.

It can be seen that the voltage during the fault happened on the 13.8 kV bus is smaller than that happened on the 230 kV bus. This can be explained by the analysis of three-phase short circuit fault. The voltage equations in [9] can be simplified as $U_{a0} = 0$, $U_{a1} = Z_f I_{a1}$, $U_{a2} = 0$. Meanwhile, the ground impedance behind the transformer is smaller than that in front of the transformer, and the symmetrical short-circuit current is limited initially only by the leakage reactance of the machine [8]. Thus the latter voltage is greater than the former one.

As mentioned before, a three-phase short circuit fault occurs on the 230 kV bus at $t = 0.1$ s, then extend the period of fault time gradually until system begins to unstable state. The result is shown in Fig. 10 (t_1 refers to the fault clearance time). Then making this process happed on the 13.8 kV bus in the same way.

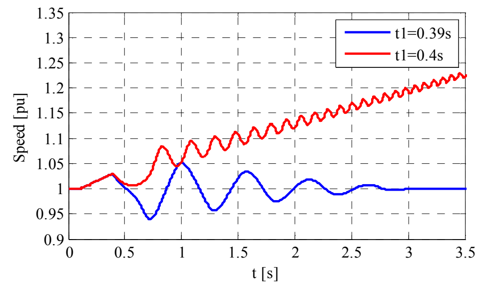

Figure 10. The influence of fault clearance time for speed.

The graph indicates that the limit clearing time of the short-circuit point behind the transformer is 0.39 s, and the limit clearing time of the short-circuit point in front of the transformer is 0.4 s which is not shown in this figure, it suggests that the system transient stability level is higher when fault happened before the transformer compared with the fault happened on the point behind the transformer, this may also demonstrate that the farther the failure away from the generator, the worse the system transient stability is.

VI. CONCLUSION

This paper uses excitation control system into a stand-alone simplified power system. It can be seen that system can achieve small oscillation stability in low frequency oscillation situation after adding the PSS, and the stabilizing effect of the PSS2A is better than the Genetic PSS. Besides, it draws following conclusions through multiple simulations and analysis of the three-phase short-circuit fault, and those may provide some reference when design of a practical synchronous generator.

1) The first amplitude of the field fault current has little to do with the phase angle while the first amplitude of the armature fault current changes periodically.

2) The armature current restores to stability after 3 s when the maximum armature fault current is about 5.43 pu and the stable time reduces to roughly 1 s when the maximum current approximately dropped to 4.55 pu.

3) The changes of maximum deviation and stable time of the rotor speed along with the length of fault duration indicate that the faster removal of the fault from the system, the smaller effect on the system.

4) The farther the failure away from the generator, the worse the system transient stability is, when using the limit clearing time to represent the system transient stability.

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