Global Journal of researches in engineering
Electrical and electronics engineering
Volume 11 Issue 6 Version 1.0 November 2011
Type: Double Blind Peer Reviewed International Research Journal
Publisher: Global Journals Inc. (USA)
Online ISSN: 2249-4596 & Print ISSN: 0975-5861

Steady State Stability Analysis of Power System under Various Fault Conditions

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GJRE-F Classification: FOR Code: 090607

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Md Multan Biswas[α] , Kamol Kanto Das[Ω]

Abstract - Stability is an important constraint in power system operation and control. Power system stability is understood as the ability to regain an equilibrium state after being subjected to a physical disturbance. This paper presents steady state stability analysis of power system and its behavior in accordance with the locations of fault. Principal among these are the determination of system stability on the consideration of Eigen values in steady state condition. This provides appropriate strategy to have a quick decision on the system's steady state behavior. The simulation results show the severity of fault and provide information to make a quick decision that whether it is possible to get the system in normal operation or not.

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I. Introduction

The steady state stability of power systems has been and continues to be of major concern in system operation. Modern electrical power systems have grown to a large complexity due to increasing of interconnections, installation of large generating units, and extra-high voltage tie-lines etc. Steady state stability refers to the ability of the power system to regain synchronism after small and slow disturbance, such as gradual power changes [1].

Economic and operational factors make power systems to utilize utmost percentage of their transmission capacity and consequently operate close to stability limit with small margins. In such environment voltage instability is emerged as a major threat for power system security. At present most of electric utilities use the fast response excitation systems, faster relays and stabilizing devices to improve the system security margin. Power systems have become increasingly concerned world-wide with voltage stability and collapse problems [2]. A number of major voltage collapse phenomena have been experienced by utilities resulted in widespread blackouts [3]. In spite of dynamic nature of voltage instability, static approaches are used for its analysis based on the fact that the system dynamics influencing voltage stability are usually slow [4]-[6].

Again, fault may occur at various locations of a power system network such as (a) near the generator, (b) middle of the transmission line, and (c) near the infinite bus etc. Steady state stability problems use a very simple generator model which treats the generator as a constant voltage source. The solution technique of steady state stability problems is to examine the stability of the system under incremental variations about an equilibrium point. The methods of linear analysis can be used to determine whether the system will remain in synchronism following small changes from the operating point or not [7]. It is convenient to assume that the disturbances causing the changes disappear. The motion of the system is free; stability is assured if the system returns to its original state. Such a behavior can be determined in a linear system by examining the characteristic equation the system.

In all stability studies, the principle objective is to determine whether or not the rotors of the machines being perturbed return to constant speed operation. Obviously this means that the rotor speeds must depart at least temporarily from synchronous speed. In the past three decades, power system stabilizers (PSSs) have been extensively used to increase the system damping for low frequency oscillations. Worldwide the power utilities are currently implementing PSSs as effective excitation controllers to improve the system stability under various faults conditions [8]–[12].

The objective of this work is to analysis a simple and effective method for stability analysis of power system under different faulty conditions by considering Eigen values in steady state condition under MATLAB environment. This research paper is organized as follows. A brief description of the system is presented in Section 2. Section 3 discusses the synchronous generator model of the considered system while the excitation system is described in Section 4. Section 5 highlights some important issues for modern prime-mover governing system. Effect of small load changes of the system and associated state variables have been summarized in Section 6. System Eigen values which play important role in determining the power system stability have been discussed in Section 7. In section 8, computer simulations are performed using the MATLAB environment under different operating conditions. Finally, some concluding remarks have been highlighted in Section 9.

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II. Description of the System

The system consists of a synchronous generator connected to the infinite bus through the parallel transmission line as shown in Fig. 1. The synchronous generator is connected to a large interconnected electric power system networks. These networks have important characteristic that the system voltage at the point of connection is constant in magnitude, phase angle, and frequency. Such a point in a power system is referred to as an infinite bus. That is, the voltage at the generator bus will not be altered by changes in the generator's operating condition [1].

Faults at different sections of the power system are considered for small disturbances and the system behavior is observed. The faults may occur (a) at the generator bus, (b) middle of the transmission line, and (c) at the infinite bus. The system is sensitive to large disturbance and may not regain synchronism.

III. Synchronous Generator Model

In the two axis model, the transient effects are accounted while the sub-transient effects are neglected. The transient effects are dominated by the rotor circuits, which are the field circuit in the d-axis and an equivalent circuit in the q-axis formed by the solid rotor. An additional assumption is made in this model is that the stator voltage equations in terms of flux linkages derivatives are negligible compared to the speed voltage terms. The machine will thus have two stator circuits and two rotor axis. However, the number of differential equations describing these circuits is reduced by two since flux linkages derivatives are neglected in stator voltage equations [13].

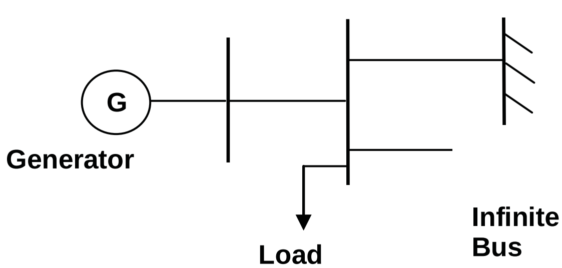


Fig. 1 : Connection of synchronous generator with an interconnected electric power system networks.

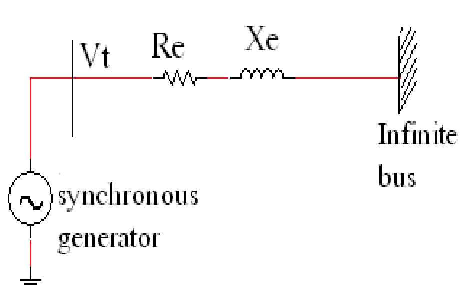


Fig. 2 : The equivalent circuit of the system.

The transient equivalent circuit of the generator is presented in Fig. 3. The following state equations have been considered:

Swing equation:-

$$\dot{\omega} = \frac{1}{M_g}\left(P_m - D_g\omega - P_e\right) \tag{1}$$

Rotor angle equations:-

$$\dot{\partial} = \omega - \omega_0 \tag{2}$$

IV. Excitation System

Each and every alternator in a power system is provided with an automatic voltage regulator. The primary function of automatic voltage regulator is to adjust the field current of the synchronous machine in an automatic way to maintain the terminal voltage at a desired value as the output of the machine varies.

Usually a high loop gain K_A renders the system unstable. Again with a small amplifier gain, automatic voltage regulator step response is not satisfactory. Thus, in order to improve the relative stability and steady state response, a stabilizing transformer is used. The input of the transformer is connected to the output of the exciter and the output is subtracted from the amplifier input. The output of the transformer is V_S. The required equations are:

$$\dot{E}_{FD} = \frac{1}{T_A}\left[-E_{FD} + \left(V_{ref} - V_t - V_s\right)K_A\right] \tag{3}$$

$$\dot{V}_s = \frac{1}{T_F}\left[-V_s + E_{FD}\right] \tag{4}$$

The armature transient voltage of direct axis and quadrature axis are expressed as,

$$\dot{E}_d' = \frac{1}{T_{qo}'}\left[-E_d' - \left(X_q - X_d'\right)I_q\right] \tag{5}$$

$$\dot{E}_q' = \frac{1}{T_{do}'}\left[E_{FD} - E_d' + \left(X_d - X_d'\right)I_d\right] \tag{6}$$

Here, E_{FD} is the field excitation voltage, T_{qo} is the d-axis transient time constant, and T_{do} is the q-axis transient time constant [3].

V. Prime-Mover Governing System

When the generator electrical load suddenly increases, the electrical power exceeds the mechanical power input. The power deficiency is supplied by the

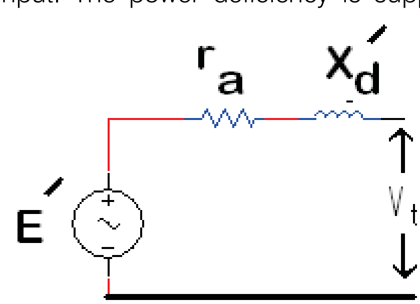


Fig. 3 : Transient equivalent circuit of the generator.

kinetic energy of the rotating system. The reduction in kinetic energy causes the turbine speed and consequently it causes the generator frequency to fall. The change in speed is sensed by the turbine governor which acts to adjust the turbine input valve to change the mechanical power output to bring the speed to a new steady state. The block diagram of modern speed governing system is shown in Fig. 4.

Here, the governor consists of two delays. Time constants of speed regulator T_{sr} = 0.1 sec. The other delay is control valve and other speed mechanism where the time constant T_{sm} = 0.2 sec. And T_{ch} is the time constant which usually lies in the range of 0.2 to 0.5 sec [3]. The equations that express the prime-mover governing system are given as,

$$\dot{P_R} = \frac{1}{T_{sr}}\left[-P_R + K_g\left(\omega_{ref} - \omega\right)\right] \tag{7}$$

$$\dot{P_h} = \frac{1}{T_{sh}}\left[-P_h + P_R\right] \tag{8}$$

$$\dot{P_{ch}} = \frac{1}{T_{ch}}\left[-P_{ch} + P_h + P_{m0}\right] \tag{9}$$

$$P_m = \frac{1}{T_{rh}}\left[-P_m + P_{ch} + \frac{K_{rh}T_{rh}}{T_{ch}}\left(-P_{ch} + P_h + P_{m0}\right)\right] \tag{10}$$

VI. Effect Of Small Load Changes (Steady State Analysis)

Steady state studies use a very simple generator model which treats the generator as a constant voltage source. Steady state stability studies are less extensive in scope and involve one or just few machines undergoing slow or gradual changes in operating conditions. The criterion of small disturbance is simply that the perturbed system can be linearized about a quiescent operating point . In general , the response of a power system to impacts current oscillatory. If the oscillations are damped, so that after sufficient time has been elapsed the deviation or the change in the state of the system due to the small impact is small, the system is stable. On the other hand if the oscillations grow in magnitude or are sustained indefinitely, the system is unstable.

When the load changes on a power system with a little amount, the system state variables are expressed as:

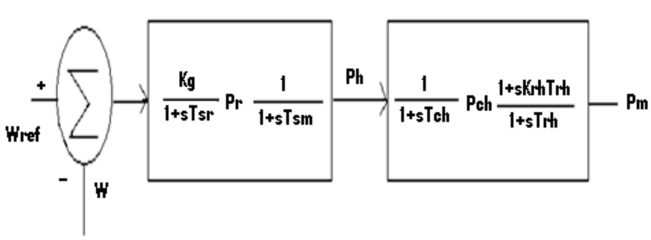


Fig. 4 : Block diagram of modern speed governing system.

$M_g\Delta\dot{\omega} = \Delta P_m - D_g\Delta\omega - I_{do}'\Delta E_d' - I_{qo}'\Delta E_q' - E_{do}'\Delta I_d - E_{qo}'\Delta I_q$

$\Delta\dot{\partial} = \omega_0\Delta\omega$

$T_A\Delta\dot{E}_{FD} = -\Delta E_{FD} + K_A(-\Delta V_s - f_1\Delta E_d' - f_2\Delta E_q' + f_3\Delta I_d + f_4\Delta I_d)$

$-K_F\Delta\dot{E}_{FD} + T_F\Delta\dot{V}s = -\Delta V_s$

$T_{qo}'\Delta\dot{E}_d' = -\Delta E_d' - (X_q - X_d')\Delta I_q$

$T_{qo}'\Delta\dot{E}_q' = \Delta E_{FD} - \Delta E_q' + (X_d - X_d')\Delta I_d$

$T_{sr}\Delta\dot{P}_R = -\Delta P_R - K_g\Delta\omega$

$T_{sm}\Delta\dot{P}_h = -\Delta P_h + \Delta P_R$

$T_{ch}\Delta\dot{P}_c = -\Delta P_c + \Delta P_h$

$-K_{rh}T_m\Delta\dot{P}_c + T_m\Delta\dot{P}_m = -\Delta P_m + \Delta P_c$

Where $f_1 = \frac{V_{do}}{V_{to}}$, $f_2 = \frac{V_{qo}}{V_{to}}$, $f_3 = f_2X_d' - f_1r_a$, $f_4 = -f_1X_d' - f_2r_a$

Consideration:

$V_{ref} = 1\,p.u.$, $\omega_0 = 1\,p.u.$, and $V_s = 0$, because under steady state no stabilizing signal is required. the above equations can be expressed in matrix form as,

$$[F][\dot{x}] = [B][X] + [D][I_{dq}]$$
$$I_{dq} = G\ L\ X$$
$$\therefore F\dot{x} = (B + D\ G\ L)X$$
$$\therefore \dot{x} = F^{-1}((B + D\ G\ L)X)$$
$$\therefore \dot{x} = A\ X$$

Finally, Eigen values are determined using MATLAB.

VII. Eigen Value Sensitivity

Eigen values play important role in determining the power system stability. Table 1 shows the system Eigen values for two initial operating conditions for reheat steam turbine gain of K_{rh} = 0.3 and K_{rh} = 2.4. Electromechanical modes are denoted in bold. The value of K_{rh} may be changed to get the electromechanical mode of oscillation and K_{rh} varies from 0.3 to 0.4. For both P_0 = 1.0 p.u. and P_0 =1.2 p.u., the system real part of the oscillatory mode is small compared to the imaginary part. On the other hand, For P_0 = 1.2 p.u. and K_{rh} = 2.4, the system has positive real part. Because of positive real part, the system will be unstable.

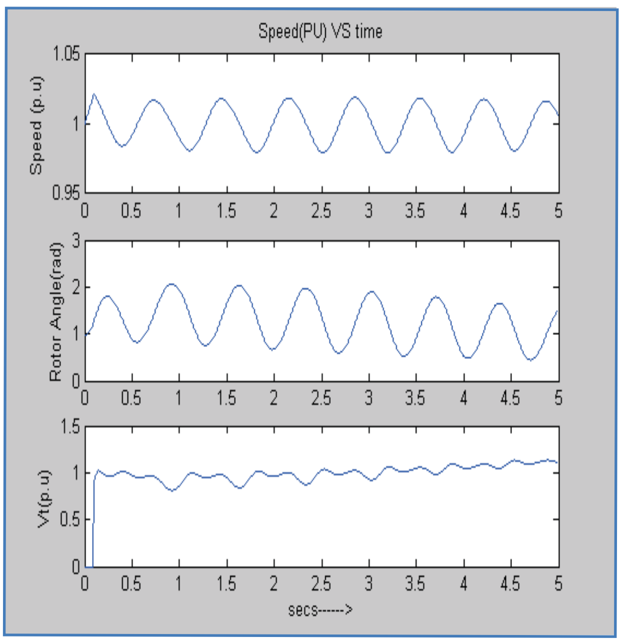
VIII. Computer Simulation

These computer simulations have been performed using the MATLAB environment under different operating conditions. The system performance is observed for different locations of the transmission line. Three case studies have been conducted.

Table 1 : System Eigen values

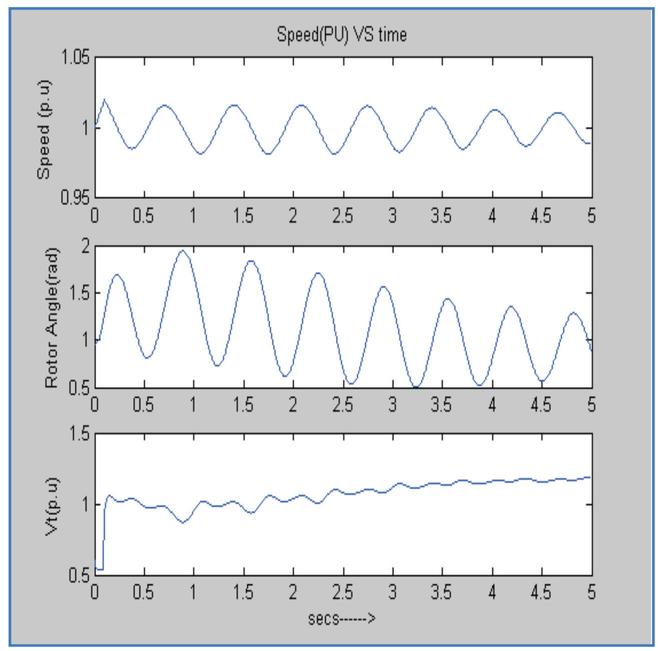
P_0 = 1.0 p.u. K_{rh} = 0.3	P_0 = 1.2 p.u. K_{rh} = 0.3	P_0 = 1.0 p.u. K_{rh} = 2.4	P_0 = 1.2 p.u. K_{rh} = 2.4
-217.8	-217.89	-217.8	-217.89
-41.55	-41.7	-41.55	-41.7
-19.94	-19.94	-19.45	-19.47
$-0.25 \pm 10.07j$	$-0.10 \pm 10.32j$	$+0.09 \pm 10.23j$	$+0.05 \pm 10.46j$
-10.22	-10.21	-11.63	-10.59
-4.9	-4.9	-4.32	-4.3
-2.3	-2.37	-2.25	-2.35
-1.49	-1.49	-1.51	-1.59
-0.12	-0.12	-0.13	-0.13

Case 1: Fault occurs at the generator bus



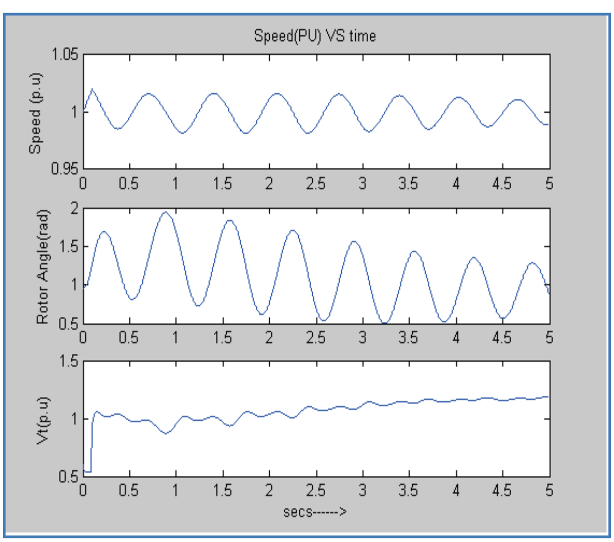
(a)

Case 2 : Fault occurs at the middle of the transmission line



(b)

Case 3 : Fault occurs at the infinite bus



(c)

Fig. 5 : System performances for different locations of faults.

IX. Conclusion

Two axis model of synchronous machine taking into account the effect of saliency is considered for steady state stability analysis. For small disturbance, it is possible to regain the stability of the system. This is observed by varying the air gap power P_e. If the forces tending to hold the machines in synchronism with one another are sufficient to overcome the disturbing forces, the system is said to remain stable. The gradual increase of the generator power output is possible until the maximum electrical power is transferred. This maximum power is referred to as the steady state stability limit. The most common boundary conditions are the terminal voltage and either the current I_a and the power factor or the generated power and the reactive power. In either case V_a, I_a and Φ (Power factor angle) are assumed to be known. In this paper, the steady state analysis is performed. The ten equations in section VI would be changed for small load changes. The initial values as well as Eigen values are calculated and finally computer simulation of the system is performed. For all cases, the initial power P_e = 1.03 is considered as the air gap power. It is observed from Fig. 5 (a) that fault at the generator bus is very much severe. It is impossible to regain the system into stable, because the speed of the rotor and the rotor angle is continuously oscillatory. Fig. 5 (b) demonstrates that fault at the middle of the transmission line is not much severe. In this case, the oscillation of the rotor angle and the speed reduces with respect to time. The system may come back into stable state. From Fig. 5 (c), it is seen that it is possible to regain synchronism. In a short time the system comes back into stable state.

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Appendix: System Data and Initial Conditions

All parameters are expressed in per unit (p.u) unless stated otherwise.

Generator and Transmission line:

Base: 160 MVA; 15 kV

Generator: 160 MVA, 15kV, 0.85 p.f.

Exciter: 375 V, 926 A

R_a=0.001096	X_d=1.7	X_d'=0.245
T_{q0}=0.075	T_{d0}=5.9	D_g=0
M_g=4.74	X_q'=.380	X_q=1.64

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