IOSR Journal of Engineering (IOSRJEN) **www.iosrjen.org**
ISSN (e): 2250-3021, ISSN (p): 2278-8719
Vol. 05, Issue 01 (January. 2015), ||V1|| PP 34-39

Solution of Swing equation for Transient Stability Analysis in Dual-machine System

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Abstract: - The stability of an interconnected power system is its ability to return to normal or stable operation after having been subjected to some form of disturbance. With interconnected systems continually growing in size and extending over vast geographical regions, it is becoming increasingly more difficult to maintain synchronism between various parts of the power system. Modern power systems have many interconnected generating stations, each with several generators and many loads. So our study is focused on multi-machine stability .

Keywords: *– Stability, Swing Equation, Transient Stability, Synchronous machine, Numerical Methods*

I. INTRODUCTION

Successful operation of a power system depends largely on the engineer's ability to provide reliable and uninterrupted service to the loads. The reliability of the power supply implies much more than merely being available. Ideally, the loads must be fed at constant voltage and frequency at all times. The first requirement of reliable service is to keep the synchronous generators running in parallel and with adequate capacity to meet the load demand. Synchronous machines do not easily fall out of step under normal conditions. If a machine tends to speed up or slow down, synchronizing forces tend to keep it in step. Conditions do arise, however, such as a fault on the network, failure in a piece of equipment , sudden application of a major load such as a steel mill, or loss of a line or generating unit., in which operation is such that the synchronizing forces for one or more machines may not be adequate, and small impacts in the system may cause these machines to lose synchronism.

A second requirement of reliable electrical service is to maintain the integrity of the power network. The high-voltage transmission system connects the generating stations and the load centers. Interruptions in this network may hinder the flow of power to the load. This usually requires a study of large geographical areas since almost all power systems are interconnected with neighboring systems.

Random changes in load are taking place at all times, with subsequent adjustments of generation. One may look at any of these as a change from one equilibrium state to another. Synchronism frequently may be lost in that transition period, or growing oscillations may occur over a transmission line, eventually leading to its tripping. These problems must be studied by the power system engineer and fall under the heading ***"power system stability"***.

II. STUDY OF SWING EQUATION

2.1 STABILITY

The tendency of a power system to develop restoring forces equal to or greater than the disturbing forces to maintain the state of equilibrium is known as "***STABILITY***".

The problem of interest is one where a power system operating under a steady load condition is perturbed, causing the readjustment of the voltage angles of the synchronous machines. If such an occurrence creates an unbalance between the system generation and load, it results in the establishment of a new steady-state operating condition, with the subsequent adjustment of the voltage angles. The perturbation could be a major disturbance such as the loss of a generator, a fault or the loss of a line, or a combination of such events. It could also be a small load or random load changes occurring under normal operating conditions. Adjustment to the new operating condition is called the transient period. The system behavior during this time is called the dynamic system performance, which is of concern in defining system stability. The main criterion for stability is that the synchronous machines maintain synchronism at the end of the transient period.

So we can say that if the oscillatory response of a power system during the transient period following a disturbance is damped and the system settles in a finite time to a new steady operating condition, we say the system is stable. If the system is not stable, it is considered unstable. This primitive definition of stability requires that the system oscillations be damped. This condition is sometimes called asymptotic stability and means that the system contains inherent forces that tend to reduce oscillations. This is a desirable feature in many systems and is considered necessary for power systems. The definition also excludes continuous oscillation from the family of stable systems, although oscillators are stable in a mathematical sense. The reason is practical since a continually oscillating system would be undesirable for both the supplier and the user of electric power. Hence the definition describes a practical specification for an acceptable operating condition. The stability problem is concerned with the behavior of the synchronous machines after a disturbance. For convenience of analysis, stability problems are generally divided into two major categories-steady state stability and transient state stability and transient state stability.

2.2 SWING EQUATION

Under normal operating conditions, the relative position of the rotor axis and the resultant magnetic field axis is fixed. The angle between the two is known as the power angle or torque angle. During any disturbance, rotor will decelerate or accelerate with respect to the synchronously rotating air gap mmf, a relative motion begins. The equation describing the relative motion is known as the swing equation.

Synchronous machine operation:

- Consider a synchronous generator with electromagnetic torque Te running at synchronous speed ωsm..
- During the normal operation, the mechanical torque Tm = Te.
- A disturbance occur will result in accelerating/decelerating torque Ta=Tm-Te (Ta>0 if accelerating, Ta<0 if decelerating).
- By the law of rotation –

$$J\frac{d^2\theta_m}{dt^2} = T_a = T_m - T_e$$

Where J is the combined moment of inertia of prime mover and generator .

- θm is the angular displacement of rotor w.r.t. stationery reference frame on the stator
- θm = ωsmt+δm, ωsm is the constant angular velocity .
- Swing equation in terms of inertial constant M

$$M\frac{d^2\delta_m}{dt^2} = P_m - P_e$$

- Relations between electrical power angle δ and mechanical power angle δm and electrical speed and mechanical speed

$$\delta = \frac{p}{2}\delta_m\ ,\ \omega = \frac{p}{2}\omega_m$$

where P is the pole number .

- Swing equation in terms of electrical power angle δ

$$\frac{2}{p}M\frac{d^2\delta}{dt^2} = P_m - P_e$$

- Converting the swing equation into per unit system

$$\frac{2H}{\omega_s}\frac{d^2\delta}{dt^2} = P_{m(pu)} - P_{e(pu)}\ ,$$

$$where\ M = \frac{2H}{\omega_s}$$

where H is the inertia constant .

III. STEADY STATE STABILITY

The ability of power system to remain its synchronism and returns to its original state when subjected to small disturbances. Such stability is not affected by any control efforts such as voltage regulators or governor.

3.1 Analysis of steady-state stability by swing equation

Starting from swing equation:-

$$\frac{Hd^2\delta}{\pi f_0 dt^2} = P_{m(pu)} - P_{e(pu)} = P_m - P_{max}sin\delta$$

$$P_s = P_{max}cos\delta_0$$

- Introduce a small disturbance Δ δ

- Derivation is from δ=δ0+Δδ
- Simplify the nonlinear function of power angle δ
- Analysis of steady-state stability by swing equation
- Swing equation in terms of Δδ

$$\frac{H}{\pi f_0}\frac{d^2\Delta\delta}{dt^2} + P_m cos\delta_0 \Delta\delta = 0$$

3.2 Damping torque:

- Phenomena: when there is a difference angular velocity between rotor and air gap field, an induction torque will be set up on rotor tending to minimize the difference of velocities.
- Introduce a damping power by damping torque :

$$P_d = D\frac{d\delta}{dt}$$

- Introduce the damping power into swing equation.
- Characteristic equation:

$$\frac{H}{\pi f_0}\frac{d^2\Delta\delta}{dt} + D\frac{d\Delta\delta}{dt} + P_s\Delta\delta = 0$$

$$\frac{d^2\Delta\delta}{dt^2} + 2\zeta\omega_n\frac{d\Delta\delta}{dt}\omega^2{}_n\Delta\delta = 0$$

- Solution of the swing equation :

$$\frac{d^2\Delta\delta}{dt^2} + 2\zeta\omega_n\frac{d\Delta\delta}{dt} + \omega^2{}_n\Delta\delta = 0$$

- Roots of swing equation :

$$\Delta\delta = \frac{\Delta\delta_0}{\sqrt{1-\zeta^2}}e^{-\zeta\omega_n t}\sin(\omega_d t + \theta)$$

$$\delta = \delta_0 + \frac{\Delta\delta_0}{\sqrt{1-\zeta^2}}e^{-\zeta\omega_n t}\sin(\omega_d t + \theta)$$

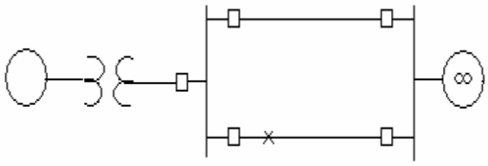

Fig.3.1 Diagram for Steady State Problem

IV. TRANSIENT STABILITY

The transient stability studies involve the determination of whether or not synchronism is maintained after the machine has been subjected to severe disturbance. This may be sudden application of load, loss of generation, loss of large load, or a fault on the system. In most disturbances, oscillations are of such magnitude that linearization is not permissible and the nonlinear swing equation must be solved.

4.1 NUMERICAL SOLUTION OF SWING EQUATION

The transient stability analysis requires the solution of a system of coupled non-linear differential equations. In general, no analytical solution of these equations exists. However, techniques are available to obtain approximate solution of such differential equations by numerical methods and one must therefore resort to numerical computation techniques commonly known as digital simulation. Some of the commonly used numerical techniques for the solution of the swing equation are:

- Point by point method
- Euler modified method
- Runge-Kutta method

In our analysis, we have used Euler modified method and Point-by Point Method.

➢ The swing equation can be transformed into state variable form as :

$$\frac{d\delta}{dt} = \Delta\omega$$
$$\frac{d\Delta\delta}{dt} = \frac{\pi f_0}{H} P_a$$

➢ We now apply modified Euler's method to the above equations as below :

$$\left.\frac{d\delta}{dt}\right| \Delta\omega^p{}_{i+1} = \Delta\omega^p{}_{i+1} \; where \; \Delta\omega^p{}_{i+1} = \Delta\omega_i + \left.\frac{d\Delta\omega}{dt}\right| \delta_i \; \Delta t$$

$$\left.\frac{d\Delta\omega}{dt}\right| \delta^p{}_{i+1} = \frac{\pi f_0}{H} P_a \Big| \delta^p{}_{i+1} \; where \; \delta^p{}_{i+1} = \delta_i + \left.\frac{d\delta}{dt}\right| \Delta\omega_i \; \Delta t$$

➢ Then the average value of the two derivatives is used to find the corrected values.

$$\delta^c{}_{i+1} = \delta_i + \left(\frac{\left.\frac{d\delta}{dt}\right| \Delta\omega_i + \left.\frac{d\delta}{dt}\right| \Delta\omega^p{}_i}{2} \right) \Delta t$$

$$\Delta\omega^c{}_{i+1} = \Delta\omega_i + \left(\frac{\left.\frac{d\Delta\omega}{dt}\right| \delta_i + \left.\frac{d\Delta\omega}{dt}\right| \delta^p{}_i}{2} \right) \Delta t$$

This is illustrated in the Simulink design.

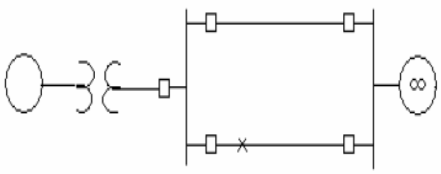

Fig.4.1 Diagram for Transient State Stability design

V. MULTI-MACHINE SYSTEM

Multi-machine system can be written similar to one-machine system by the following assumptions:

- Each synchronous machine is represented by a constant voltage E behind Xd (neglect saliency and flux change) .
- Input power remain constant .
- Using pre-fault bus voltages, all loads are in equivalent admittances to ground .
- Damping and asynchronous effects are ignored
- δmech = δ
- Machines belong to the same station swing together and are said to be coherent, coherent machines can equivalent to one machine .

Solution to multi-machine system:

- Solving initial power flow and determine initial bus voltage magnitude and phase angle

$$I_i = \frac{S^*{}_i}{V^*{}_i} = \frac{jQ_i}{V^*{}_i},$$
$$E'{}_i = V_i + jX'{}_i I_i$$

➢ Calculating load equivalent admittance

$$y_{io} = \frac{P_i - jQ_i}{|V_i|^2}$$

➢ Nodal equations of the system

$$\begin{bmatrix} 0 \\ I_m \end{bmatrix} = \begin{bmatrix} Y_{nn} & Y_{nm} \\ Y^t{}_{nm} & Y_{mm} \end{bmatrix} \begin{bmatrix} V_n \\ E'{}_m \end{bmatrix}$$

➢ Electrical and mechanical power output of machine at steady state prior to disturbances.

- Classical transient stability study is based on the application of the three-phase fault

$$P_{ei} = P_{mi} = R_e\{\acute{E}_i, I_i\} = \sum_{j=1}^{m} |\acute{E}_i||\acute{E}_j||Y_{ij}|\cos(\theta_{ij} - \delta_i + \delta_j)$$

- Swing equation of multi-machine system

$$\frac{H_i}{\pi f_0}\frac{d^2\delta_i}{dt^2} = P_{mi} - \sum_{j=1}^{m} |\acute{E}_i||\acute{E}_j||Y_{ij}|\cos(\theta_{ij} - \delta_i + \delta_j) = P_{mi} - P_{ei}$$

- Y_{ij} are the elements of the faulted reduced bus admittance matrix
- State variable model of swing equation

$$\frac{d\delta_i}{dt} = \Delta\omega_i\,, \quad i = 1, K, n$$

$$\frac{d\Delta\omega_i}{dt} = \frac{\pi f_0}{H_i}(P_{mi} - P_{ei})$$

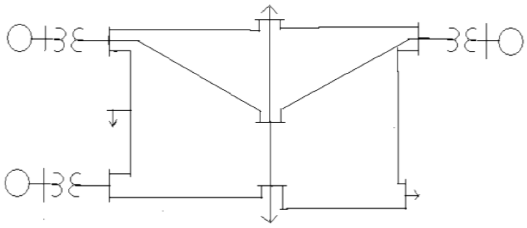

Fig.5.1 Diagram for Dual-machine Stability

VI. SIMULATION

For our simulation we have taken a Power System Network of a electrical company shown in fig.5.1 . The values of load data, voltage magnitude, generation schedule and the reactive power limits for the regulated buses are suitably taken. Bus 1 of the system is carefully considered with a specified value and is taken as slack bus . The data for basemva, accuracy, mailer, bus data, line data and gendata are suitably taken in matrix form . The whole process of simulation is carried out by using MATLAB-7.0.

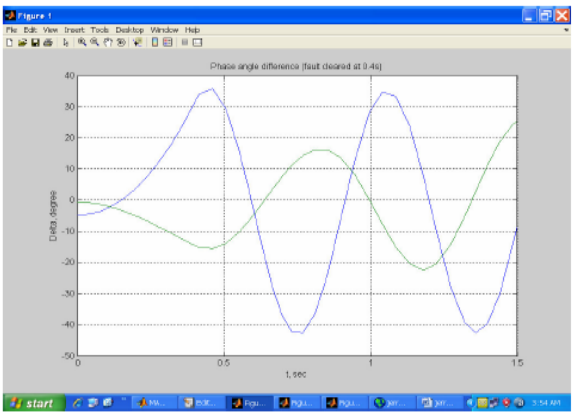

Fig.6.1 Dual-machine Stability for Fault cleared at 0.4Sec .

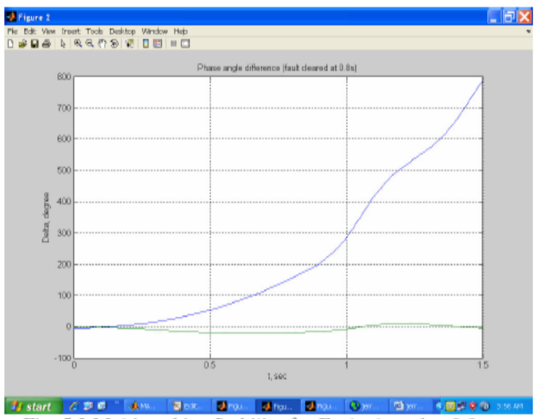

Fig.6.2 Dual-machine Stability for Fault cleared at 0.8Sec .

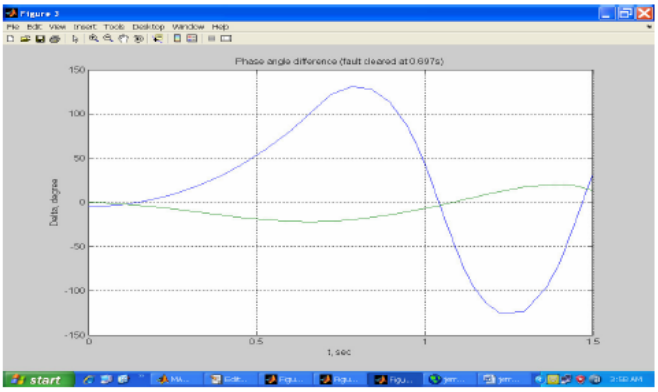

Fig.6.3 Dual-machine Stability for Fault cleared at 0.697Sec .

VII. RESULT ANALYSIS

- Phase angle differences, after reaching a maximum of δ21=123.90 and
- δ31=62.950 will decrease, and the machines swing together.
- Hence, the system is found to be stable when fault is cleared in 0.4 second.
- The swing curves shown in figure show that machine 2 phase angle increases without limit.
- Thus, the system is unstable when fault is cleared in 0.5 second.
- The simulation is repeated for a clearing time of 0.45 second which is found to be critically stable.

VIII. CONCLUSIONS

It can be seen that transient stability is greatly affected by the type and location of a fault so that a power system analyst must at the very outset of a stability study decide on these two factors. Thus we saw that a two-machine system can be equivalently reduced to a one machine system connected to infinite bus bar. In case of a large multi-machine system, to limit the computer memory and time requirements, the system is divided into a study subsystem and an external subsystem. The study subsystem is modelled in details whereas approximate modelling is carried out for the rest of the subsystem. The qualitative conclusions regarding system stability drawn from a two-machine or an equivalent one-machine infinite bus system can be easily extended to a multi-machine system. It can be seen that transient stability is greatly affected by the type and location of a fault so that a power system analyst must at the very outset of a stability study decide on these two factors. The solution of swing equation in Small Signal Stability Including Effects of Rotor Circuit Dynamics in synchronous machine will be the future work.

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