

Representation of Transient Stability for Power System Dynamics Using Numerical Integration Method and Damping

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ABSTRACT

Analysis of transient stability of power systems involves the computation of their nonlinear dynamic response to large disturbances, usually a transmission network fault, followed by the isolation of the faulted element by protective relaying. For transient stability analysis, non-linear system equations are solved. In addition, large discontinuities due to faults and network switching and small discontinuities due to limits on system variables appear in the system model. Bus voltages, line flows and performance of protection systems are of interest in addition to the basic information related to the stability of the system. In this paper detailed transient stability analysis is done whereby the classical model is slightly improved upon by taking into account the effect of damping towards transient stability response. Characteristics of the various components of a power system during normal operating conditions and during disturbances have been examined, and effects on the overall system performance are analyzed.

Keywords: - Transient Stability, damping, short circuit fault, Synchronous machine etc.

1. INTRODUCTION

Representation of transient stability of power systems involves the computation of their nonlinear dynamic response to large disturbances, usually a transmission network fault, followed by the isolation of the faulted element by protective relaying. Considering the system shown in figure-1.1 consisting of a generator delivering power to a large system represented by an infinite bus through transmission circuits. An infinite bus represents a voltage source of constant voltage magnitude and constant frequency.

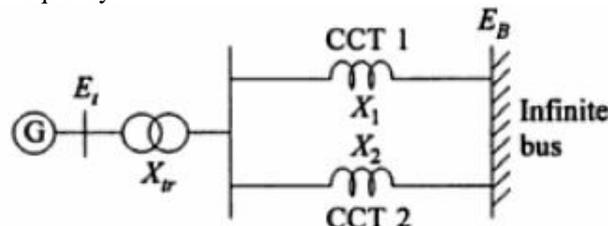


Figure 1.1: Single machine infinite bus system

The fundamental concepts and principles of transient stability can be represented by analyzing the system response to large disturbances, using very simple models. All resistances are neglected. The generator is represented by the classical model (figure-1.1) and the speed governor effects are neglected.

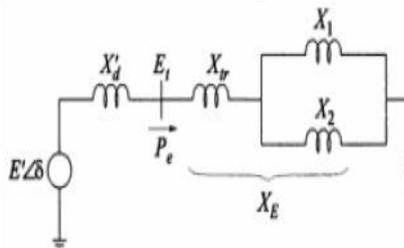


Figure 1.2: Equivalent Circuit

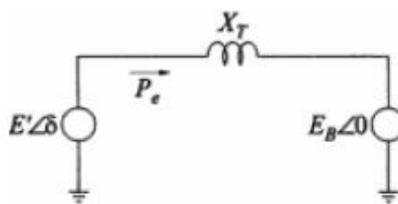


Figure 1.3: Reduced equivalent Circuit

The corresponding system representation is shown in Figure-1.2. The voltage behind the transient reactance (X_d') is denoted by E' . The rotor angle represents the angle by which E' leads E_B . When the system is perturbed, the magnitude of E' remains constant at its pre disturbance value and δ changes as the generator rotor speed deviates from synchronous speed ω_0 . The system model can be reduced to the form shown in Figure-1.3. It can be analyzed by using simple analytical methods and is helpful in acquiring a basic understanding of the transient stability phenomenon.

The generator's electrical output is:

$$P_e = \frac{E' E_B}{X_T} \sin\delta = P_{max} \sin\delta \quad \text{or} \quad P_{max} = \frac{E' E_B}{X_T}$$

Since the stator resistance was neglected, P_e represents the air-gap power as well as the terminal power.

2. RESPONSE TO A STEP CHANGE IN MECHANICAL POWER

Let us now examine the transient behavior of the system, with both circuits in service, by considering a sudden increase in the mechanical power input from an initial value of P_{m0} to P_{m1} as shown in Figure 2.1.

- Because of the inertia of the rotor, the rotor angle cannot change instantly from the initial value of δ_0 to δ_1 corresponding to the new equilibrium point b at which $P_e = P_{m1}$.
- The mechanical power is now in excess of the electrical power.
- The resulting accelerating torque causes the rotor to accelerate from the initial operating point a toward the new equilibrium point b , tracing the P_e - δ curve at a rate determined by the swing equation.
- The difference between P_{m1} and P_e at any instant represents the accelerating power.
- When point b is reached, the accelerating power is zero, but the rotor speed is higher than the synchronous speed ω_0 (which corresponds to the frequency of the infinite bus voltage). Hence, the rotor angle continues to increase.
- For values of δ higher than δ_1 , P_e is greater than P_{m1} and the rotor decelerates. At some peak value δ_m , the rotor speed recovers to the synchronous value ω_0 , but P_e is higher than P_{m1} .
- The rotor continues to decelerate with the speed dropping below ω_0 ; the operating point retraces the P_e - δ curve from c to b and then to a .
- The power system in the above analysis is neglected all resistances and the classical model is used to represent the generator. In effect, this neglects all sources of damping.
- Therefore, the rotor oscillates continue unabated following the perturbation. There are many sources of positive damping including field flux variations.
- In a system which is small-signal stable, the oscillations damp out.

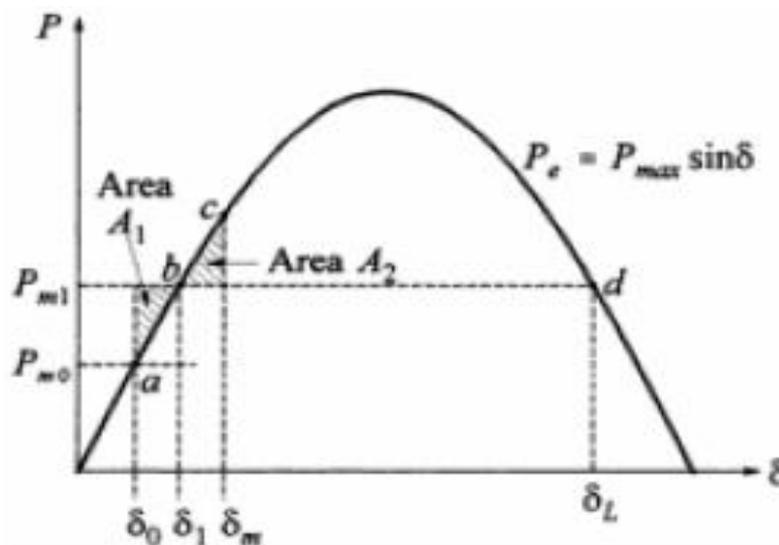


Figure 2.1: Power Angle Variations

3. RESPONSE TO A SHORT CIRCUIT FAULT

If it considered the response of the system to a three-phase fault at location 'F' on transmission circuit, the fault is cleared by opening circuit breakers at both the ends of the faulted circuit and the fault clearing time depending upon the relaying time and breaker time.

If the fault location F is at the sending end (HT bus) of the faulted circuit, no power is transmitted to the infinite bus. The short-circuit current from the generator flows through pure Reactance's to the fault. Hence, only reactive power flows and the active power P_e and the corresponding electrical torque T_e at the air-gap are zero during the fault. If we had included generator stator and transformer resistances in our model P_e would have a small value, representing the corresponding resistive losses. If the fault location F is at some distance away from the sending end some active power is transmitted to the infinite bus while the fault is still on.

The network conditions are : (i) pre fault (both circuits in service) (ii) with a three phase fault on circuit 2 at a location some distance from the sending end and (iii) post fault (circuit 2 out of service)

4. FACTORS INFLUENCING TRANSIENT STABILITY

Transient stability of the generator is dependent on the following:

- (a) How heavily the generator is loaded
- (b) The generator output during fault. This depends on the fault location and type
- (c) The fault-clearing time
- (d) The post fault transmission system reactance
- (e) The generator reactance. A lower reactance increases peak power and reduces initial rotor angle.
- (f) The generator inertia: The higher the inertia, the slower the rate of change in angle. This reduces the kinetic energy gained during fault; i.e., area A1 is reduced.
- (g) The generator internal voltage magnitude ('E'). This depends on the field excitation.
- (h) The infinite bus voltage magnitude EB

As a means of introducing basic concepts, a system was considered having a simple configuration and represented by a simple model. This has enabled the analysis of stability by using a graphical approach. I have not actually computed them, and hence the time scales have not been defined for these plots. Practical power systems have complex network structures. Accurate analysis of their transient stability requires detailed models for generating units and other equipment. At present, the most practical available method of transient stability analysis is time-domain simulation in which nonlinear differential equations are solved by using step-by-step numerical integration techniques.

5. NUMERICAL INTEGRATION METHODS

The differential equations to be solved in power system stability analysis are nonlinear ordinary differential equations with known initial values:

$$\frac{dx}{dt} = f(x, t)$$

Here x is the state vector of n - dependent variables and t is the independent variable (time). The objective is to solve x as a function of t , with the initial values of x and t equal to x_0 and t_0 respectively.

In this section general description was provided of numerical integration methods applicable to the solution of equations of the above form. In describing these methods, without loss of generality, I'll treat above equation as if it were a first order differential equation.

5.1 Runge-Kutta (R-K) Methods

The R-K methods approximate the Taylor series solution; however, unlike the formal Taylor series solution, the R-K methods do not require explicit evaluation of derivatives higher than the first. The effects of higher derivatives are included by several evaluations of the first derivative. Depending on the number of terms effectively retained in the Taylor series, I have R-K methods of different orders.

5.1.1 Second Order R-K Method

Referring to the above differential equation, the second order R-K formula for the value of x at $t = t_0 + \Delta t$ is:

$$x_1 = x_0 + \Delta x = x_0 + (k_1 + k_2)/2 \Delta t$$

Where

$$k_1 = f(x_0, t_0) \Delta t$$
$$k_2 = f(x_0 + k_1, t_0 + \Delta t) \Delta t$$

This method is equivalent to considering first and second derivative terms in the Taylor series; error is on order of Δt^3 . A general formula giving the value of x for $(n + 1)$ st step is,

$$x_{n+1} = x_n + (k_1 + k_2)/2 \Delta t$$

Where

$$k_1 = f(x_n, t_n) \Delta t$$
$$k_2 = f(x_n + k_1, t_n + \Delta t) \Delta t$$

5.1.2 Fourth Order R-K Method

The general formula giving the value of x for the $(n + 1)$ st step is,

$$x_{n+1} = x_n + (k_1 + 2k_2 + 2k_3 + k_4)/6 \Delta t$$

where

$$k_1 = f(x_n, t_n) \Delta t$$
$$k_2 = f(x_n + k_1/2, t_n + \Delta t/2) \Delta t$$
$$k_3 = f(x_n + k_2/2, t_n + \Delta t/2) \Delta t$$
$$k_4 = f(x_n + k_3, t_n + \Delta t) \Delta t$$

The physical interpretation of the above solution is as follows:

k_1 = (slope at the beginning of time step) Δt

k_2 = (first approximation to slope at midstep) Δt

$k_3 =$ (second approximation to slope at midstep) Δt

$k_4 =$ (slope at the end of step) Δt

$\Delta x = (k_1 + 2k_2 + 2k_3 + k_4)/6$

Thus Δx is the incremental value of x given by the weighted average of estimates based on slopes at the beginning, midpoint, and end of the time step. This method is equivalent to considering up to fourth derivative terms in the Taylor series expansion; it has an error on the order of Δt^5 .

6. STEPS AND DATA TAKEN FOR SIMULATION

- Transient stability of a thermal generating station consisting of four 555 MVA, 24KV, 60 Hz units supplying power to an infinite bus is examined through two transmission circuits as shown in Figure-6.1.

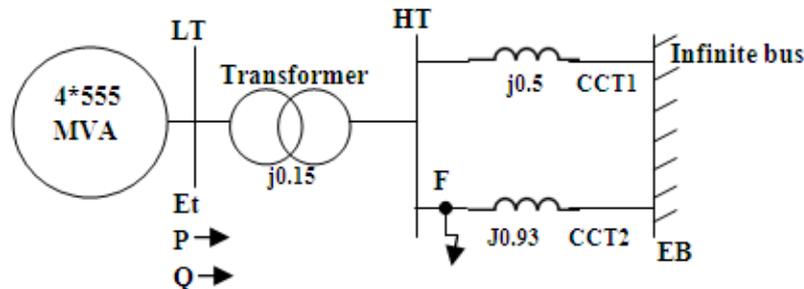


Figure 6.1: Equivalent circuit of the thermal generating station

- The network reactance shown in the figure are in per unit on 2220 MVA, 24 kV base (referred to the LT side of the step-up transformer).
- Resistances are assumed to be negligible.
- The initial system operating condition, with quantities expressed in per unit on 2220 MVA and 24 kV base is, $P = 0.9$, $Q = 0.436$ (overexcited), $E_t = 1.0 \angle 28.34^\circ$ and $E_B = 0.9008 \angle 10$
- The generators are modelled as a single equivalent generator represented by the classical model with the following parameters expressed in per unit on 2220 MVA, 24 kV base:

$$X_{d'} = 0.3, H = 3.5 \text{ MW.s/MVA and } K_D = 0.$$

- Circuit 2 experiences a solid three-phase fault at point F, and the fault is cleared by isolating the faulted circuit.
- Determination of the critical fault clearing time and the critical clearing angle by computing the time response of the rotor angle, using numerical integration.

7. RESULTS

The generator represented by the classical model, the reduced equivalent circuit representing the three system conditions: Pre-fault, during fault and post fault.

Critical clearing time = 0.22 seconds

Critical clearing angle = 52.23 degrees

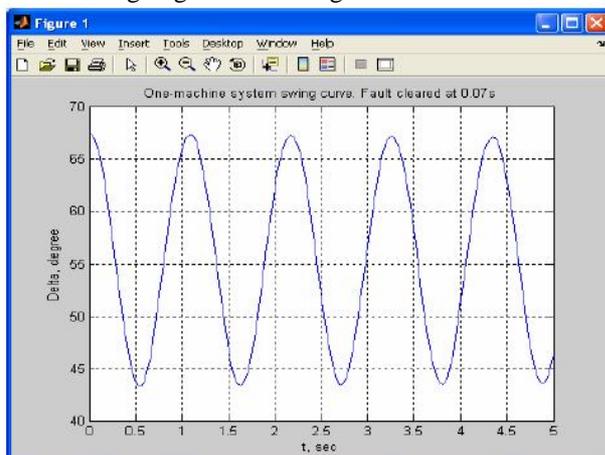


Figure 7.1: One machine System Swing Curve fault cleared at 0.07 seconds

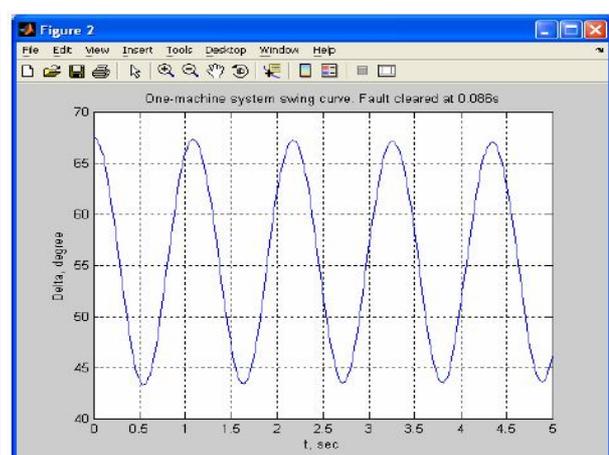


Figure 7.2: One machine System Swing Curve fault cleared at 0.086 seconds

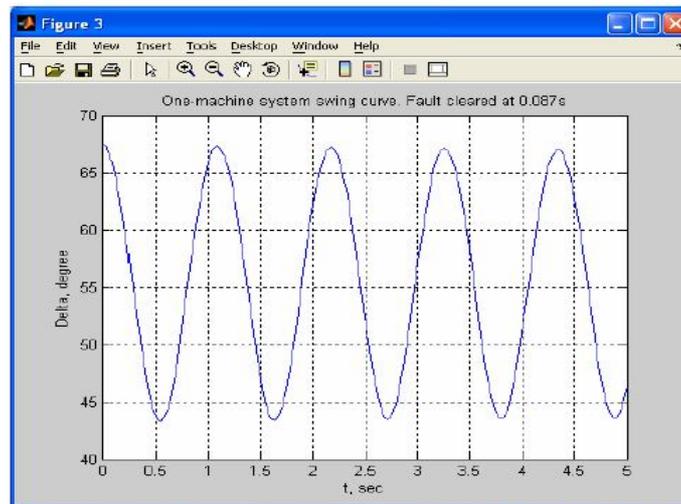


Figure 7.3: One machine System Swing Curve fault cleared at 0.087 seconds

8. SIMULATION FOR POWER SYSTEM DYNAMIC RESPONSE

8.1 Structure of the Power System Model

Analysis of transient stability of power systems involves the computation of their nonlinear dynamic response to large disturbances, usually a transmission network fault, followed by the isolation of the faulted element by protective relaying.

For transient stability analysis, non-linear system equations are solved. In addition, large discontinuities due to faults and network switching and small discontinuities due to limits on system variables appear in the system model. Bus voltages, line flows and performance of protection systems are of interest in addition to the basic information related to the stability of the system.

The overall system representation includes models for the following individual components:

- Synchronous generators and the associated excitation systems and prime movers .
- Interconnecting transmission network including static loads .
- Induction and synchronous motor loads .
- Other devices such as HVDC converters and SVCs

The model used for each component should be appropriate for transient stability analysis and the system equations must be organized in a form suitable for applying numerical methods. The complete system model consists of a large set of ordinary differential equations and large sparse algebraic equations. The transient stability analysis is thus a differential algebraic initial-value problem.

8.2 Synchronous Machine Representation including Damping

To illustrate the implementation of the generator model for transient stability analysis, it is assumed that the generator is represented by a model with one d -axis and two q -axis amortisseurs. The summary of the synchronous machine equations as a set of first order differential equations, with time t in seconds, rotor angle δ in electrical radians, and all other quantities in per unit. Where $\omega_0 = 2\pi f_0$ electrical radian/sec , $\Delta\omega_r = \text{pu rotor speed deviation}$ and $P = \text{derivative operator } d/dt$

9. STEPS TAKEN FOR SIMULATION

- Transient stability of the system by considering the previous example was analysed.
- Including more detailed model which would take into consideration the effects of damping at various stages.
- Which is consolidated and included as a parameter with constant KD in the equation of motion?
- The new system is simulated in MATLAB and the resulting transient response is displayed.

10. RESULT & ANALYSIS

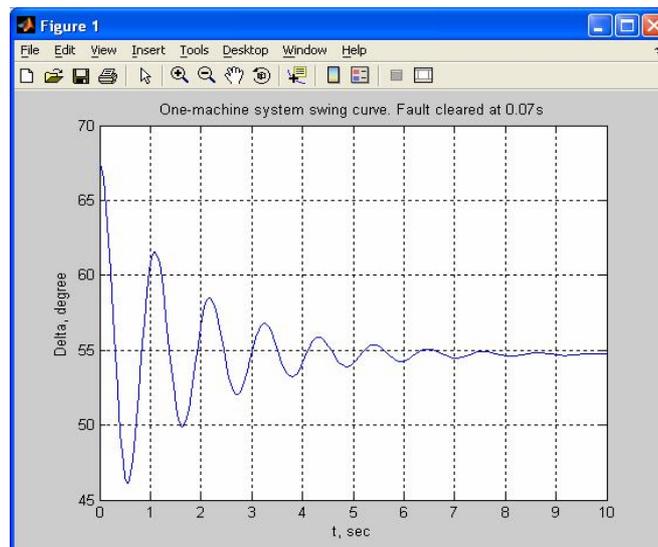


Figure 10.3: One machine System Swing Curve fault cleared at 0.07 seconds

- The waveform clearly shows that the effect of damping on the dynamic response of the system.
- The damping factor used is $KD=0.02$.
- The oscillations are clearly damped almost completely within a few cycles which give a better idea about stability.

11. CONCLUSION

Detailed transient stability analysis is done whereby the classical model is slightly improved upon by taking into account the effect of damping towards transient stability response. Characteristics of the various components of a power system during normal operating conditions and during disturbances have been examined and effects on the overall system performance are analyzed. With the trend to reduce machine inertias there is a constant need to determine availability, feasibility and applicability of new methods for maintaining and improving stability.

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