TRANSIENT STABILITY ANALYSIS USING EQUAL AREA CRITERION USING SIMULINKMODEL

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE DEGREE OF BACHELOR IN TECHNOLOGY IN ELECTRICAL ENGINEERING

Department of Electrical Engineering
National Institute of Technology
Rourkela

2008-09

Submitted by:

Ankit Jha	10502003
Lalthangliana Ralte	10502033
Ashwinee Kumar	10502037
Pinak Ranjan Pati	10402038

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Under the guidance of
Prof. SANDIP GHOSH

Submitted by:

Ankit Jha	**10502003**
Lalthangliana Ralte	**10502033**
Ashwinee Kumar	**10502037**
Pinak Ranjan Pati	**10402038**

National Institute Of Technology
Rourkela

CERTIFICATE

This is to certify that the thesis entitled, **"Transient system analysis and control of power systems"** submitted by **Ankit Jha , Lalthangliana Ralte, Ashwinee Kumar and Pinak Ranjan Pati** at the National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by them under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree or Diploma.

Prof Sandip Ghosh

Date: 10.05.2009 **Dept. of Electrical engineering**

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This project is by far the most significant accomplishment in our life and it would be impossible without people who supported us and believed in us.

We would like to extend our gratitude and our sincere thanks to our honorable, esteemed supervisor **Prof. Sandip Ghosh,** Department of Electrical Engineering. He is not only a helpful Prof. with deep vision but also most importantly a kind person. We sincerely thank for his exemplary guidance and encouragement. His trust and support inspired us in the most important moments of making right decisions and we are glad to work with him.

We would like to thank all my friends for all the thoughtful and mind simulating discussion we had, which make us to think beyond the obvious.

We would like to thank all those who made me stay in Rourkela an unforgettable and rewarding experience.

Last but not least we would like to thank our parents, who taught us the value of hard work by their own example. They rendered us enormous support during the whole tenure of my stay in NIT Rourkela.

Ankit Jha

Ashwinee Kumar

Lalthangliana Ralte

Pinak Ranjan Pati

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ABSTRACT

Power-system stability is a term applied to alternating-current electric power systems, denoting a condition in which the various synchronous machines of the system remain in synchronism, or "in step," with each other. Conversely, *instability* denotes a condition involving loss of synchronism, or falling **"***out of step***."** Occurrence of a fault in a power system causes transients. To stabilize the system load flow analysis is done. Actually in practice the fault generally occurs in the load side. As we controlling load side which will lead to complex problem in order to avoid that we are controlling the generator side.

A MATLAB simulation has been carried out to demonstrate the performance of the three-machine nine-bus system.

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Chapter 1

INTRODUCTION

1.1 BACKGROUND

The classical model of a multi machine may be used to study the stability of a power system for a period of time during which the system dynamic response is dependent largely on the kinetic energy in the rotating masses. The classical three-machine nine-bus system is the simplest model used in studies of power system dynamics and requires of minimum amounts of data. Hence such studies can be connected in a relatively short time under minimum cost. Among various method of load flow calculation Newton Raphson method is chosen for calculation of load flow study.

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 should be damped. This condition is sometimes called asymptotic stability and means that the system contains inherent forces that tend to reduce oscillation.

1.2 LITERATURE RIVIEW

In recent years, energy, environment, right-of-way, and cost problems have delayed the construction of both generation facilities and new transmission lines, while the demand for electric power has continued to grow. This situation has necessitated a review of the traditional power system concepts and practices to achieve greater operating flexibility and better utilization of existing power systems.

1.3 MOTIVATION OF THE PRESENT WORK

Transient stability of a transmission is a major area of research from several decades. Transient stability restores the system after fault clearance. Any unbalance between the generation and load initiates a transients that causes the rotors of the synchronous machines to “swing” because net accelerating torques are exerted on these rotors. If these net torques are sufficiently large to cause some of the rotors to swing far enough so that one or more machines “slip a pole” and synchronism is lost. So the calculation of transient stability should be needed. A system load flow analysis is required for it .The transient stability needs to be enhanced to optimize the load ability of a system, where the system can be loaded closer to its thermal limits.

1.4 PROBLEM STATEMENT

Occurrence of fault may lead to instability in a system or the machine fall out of synchronism. Load flow study should be done to analyze the transient stability of the power system. If the system can't sustain till the fault is cleared then the fault instabilise the whole system. If the oscillation in rotor angle around the final position go on increasing and the change in angular speed during transient condition go on increasing then system never come to its final position. The unbalanced condition or transient condition may leads to instability where the machines in the power system fall out of synchronism. Calculation of load flow equation by Newton Raphson method, Runge Kutta method, and decoupled method gives the rotor angle and initial condition.

1.5 THESIS ORGANISATION

Chapter 2 describes an overview of transient stability and its various physical implications in the power system i.e. mechanical analogy, an elementary view of transient stability, swing equation and its ramifications in the power system and the theory behind equal area criterion. Chapter 3 describes the control strategies adapted in the power system to nullify the effects of transient phenomenon in the system. The basic strategies/techniques are highlighted in this chapter and explained on an elementary level. The analysis is also a grand computing challenge and it has been vividly emphasized in the text as emphasized in Chapter 3. The automatic generation control strategies have been explained and it has been clearly mentioned in the chapter. Chapter 4 deals with the simulation and modeling of the power system to observe the behavior of the system when it is exposed to faulty conditions in 1of its phase. Transient analysis is carried out similarly and the observations and results are plotted out. Finally the chapter 5 deals with the conclusion and its future scope in the power systems. After that references have been given a place in the thesis without the help of which this thesis could not be completed.

Chapter 2

TRANSIENT STABILITY: AN OVERVIEW

2.1 TRANSIENT STABILITY

Each generator operates at the same synchronous speed and frequency of 50 hertz while a delicate balance between the input mechanical power and output electrical power is maintained. Whenever generation is less than the actual consumer load, the system frequency falls. On the other hand, whenever the generation is more than the actual load, the system frequency rise. The generators are also interconnected with each other and with the loads they supply via high voltage transmission line.

An important feature of the electric power system is that electricity has to be generated when it is needed because it cannot be efficiently stored. Hence using a sophisticated load forecasting procedure generators are scheduled for every hour in day to match the load. In addition, generators are also placed in active standby to provide electricity in times of emergency. This is referred as spinning reserved.

The power system is routinely subjected to a variety of disturbances. Even the act of switching on an appliance in the house can be regarded as a disturbance. However, given the size of the system and the scale of the perturbation caused by the switching of an appliance in comparison to the size and capability of the interconnected system, the effects are not measurable. Large disturbance do occur on the system. These include severe lightning strikes, loss of transmission line carrying bulk power due to overloading. The ability of power system to survive the transition following a large disturbance and reach an acceptable operating condition is called *transient stability*.

The physical phenomenon following a large disturbance can be described as follows. Any disturbance in the system will cause the imbalance between the mechanical power input to the generator and electrical power output of the generator to be affected. As a result, some of the generators will tend to speed up and some will tend to slow down. If, for a particular generator, this tendency is too great, it will no longer remain in synchronism with the rest of the system and will be automatically disconnected from the system. This phenomenon is referred to as a generator going out of step.

Acceleration or deceleration of these large generators causes severe mechanical stresses. Generators are also expensive. Damage to generators results in costly overhaul and long downtimes for repair. As a result, they are protected with equipment safety in mind. As soon as a generator begins to go out-of-step, sensor in the system sense the out-of-step condition and trip the generators. In addition, since the system is interconnected through transmission lines, the imbalance in the generator electrical output power and mechanical input power is reflected in a change in the flows of power on transmission lines. As a result, there could be large oscillations in the flows on the transmission lines as generator try to overcome the imbalance and their output swing with respect to each other.

2.2 MECHANICAL ANALOGY

A mechanical analogy to this phenomenon can be visualized in fig. 1. Suppose that there is a set of balls of different sizes connected to each other by a set of strings. The balls represent generators having a specific mechanical characteristic (that is, inertia). The strings represent the transmission line interconnecting the generators.

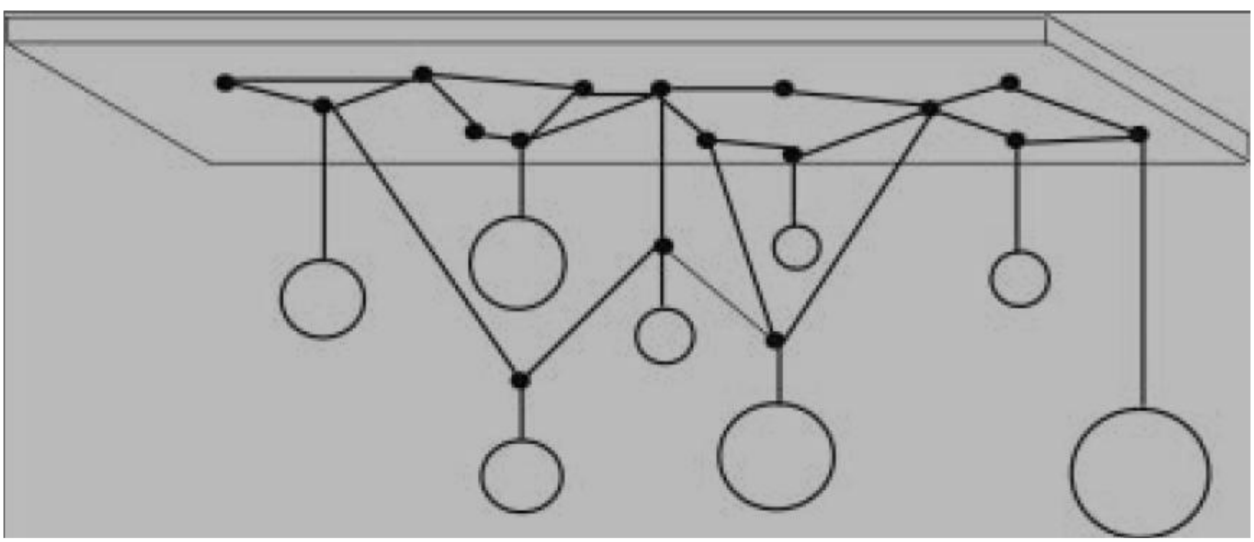


Fig.2.1. Mechanical Analogy of Transient Stability

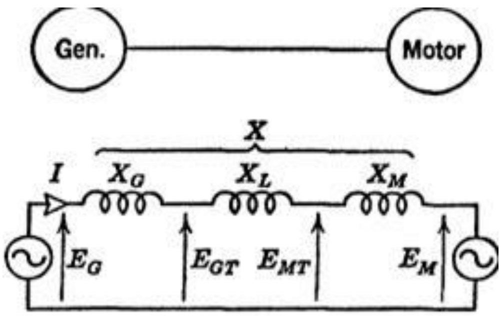
Now suppose that there is a disturbance in which one of the balls is struck with a cue. The ball now begins to swing, and as a result, the string connected to the ball also oscillates. In addition, the other strings to which this string is connected are also affected, and this in turn affects the other balls connected to these strings. As a result, the entire interconnected system of balls is affected, and the system experiences oscillations in the strings and motion of the balls. If these oscillations in the strings become large, one of the strings may break away from the rest, resulting instability. On the other hand if the oscillation dies down and the entire system comes back to rest as in the situation prior to the ball being struck. This condition is analogous to a power system being “transiently stable”.

In a power system, an additional important characteristic in the operating condition, as the loading on the system increases, the system becomes more stressed and operates closer to its limits. During these stressed condition, a small disturbance can make the system unstable. Dropping a marble into a pitcher of water provides a suitable analogy to understand why the operating condition makes a difference in maintaining transient stability.

1. Take a pitcher and fill it with the water to quarter its capacity. Now drop a marble in the pitcher. The dropping of the marble is akin to a disturbance in the power system. In this situation no water from the pitcher will splash out, indicating the system is stable.
2. Now fill the pitcher with water close to it brim and drop the same marble into the pitcher. In this case, water will splash out, indicating the system is unstable.

In these two situations, the same disturbance was created. However, the system was operating at different conditions, and in the latter situation, the system was more stressed. Again, this analogy illustrates that the degree of stability is dependent on the initial operating condition.

2.3 ELEMENTARY VIEW OF TRANSIENT STABILITY



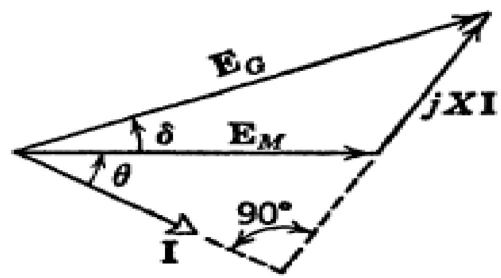


Fig. 2.2. Simple two machine power system

Fig.2.3. Phasor diagram of the different parameters

Consider the very simple power system of Fig. 2.2, consisting of a synchronous generator supplying power to a synchronous motor over a circuit composed of series inductive reactance X_L. Each of the synchronous machines may be represented, at least approximately, by a constant-voltage source in series with a constant reactance. Thus the generator is represented by *Eg* and *Xg*; and the motor, by E_M and X_M. Upon combining the machine reactance and the line reactance into a single reactance, we have an electric circuit consisting of two constant-voltage sources, *Eg* and E_M, connected through reactance $X = X_G + X_L + X_M$. It will be shown that the power transmitted from the generator to the motor depends upon the phase difference *8* of the two voltages E_G and E_M. Since these voltages are generated by the flux produced by the field windings of the machines, their phase difference is the same as the electrical angle between the machine rotors.

The vector diagram of voltages is shown in Fig. 2.3 Vectorially,

$$\boldsymbol{E}_G = \boldsymbol{E}_M + jX\boldsymbol{I}$$

(The bold-face letters here and throughout the book denote complex, or vector, quantities).

Hence the current is $$\mathbf{I} = \frac{\mathbf{E}_G - \mathbf{E}_M}{jX} \qquad (2.1)$$

The power output of the generator and likewise the power input of the motor, since there is no resistance in the line is given by

$$P = \mathrm{Re}\left(\overline{E}_g I\right)$$

$$= \mathrm{Re}\left(\overline{E}_g \frac{E_g - E_m}{jX}\right) \qquad (2.2)$$

where Re means "the real part of" and $\overline{E_G}$ means the conjugate of E_G. Now let

$$E_M = E_M\angle 0 \tag{2.3}$$

And $$E_G = E_G\angle\delta \tag{2.4}$$

Then $$\overline{E}_G = E_G\angle(-\delta) \tag{2.5}$$

So, $$P = \operatorname{Re}\left(E_G\angle-\delta\,\frac{E_G\angle\delta - E_M\angle 0}{X\angle 90^0}\right)$$

$$= \operatorname{Re}\left(\frac{E_G^2}{X}\angle(-90^0) - \frac{E_G E_M}{X}\angle(-90^0-\delta)\right)$$

$$= -\frac{E_G E_M}{X}\cos(-90^0-\delta)$$

$$= \frac{E_G E_M}{X}\sin\delta \tag{2.6}$$

This equation shows that the power *P* transmitted from the generator to the motor varies with the sine of the displacement angle δ between the two rotors, as plotted in Fig. 2.3. The curve is known as a *power angle curve*. The maximum power that can be transmitted in the steady state with the given reactance *X* and the given internal voltages *EG* and *EM* is

$$P_m = \frac{E_G E_M}{X}$$

and occurs at a displacement angle *8* = 90°. The value of maximum power may be increased by raising either of the internal voltages or by decreasing the circuit reactance.

2.4 SWING EQUATION

The electromechanical equation describing the relative motion of the rotor load angle (δ) with respect to the stator field as a function of time is known as ***Swing equation***.

$$M\frac{d^2\delta}{dt^2} = P_t - P_u \quad (2.7)$$

M= inertia constant

P_t =Shaft power input corrected for rotational losses

$P_u = P_m \sin\delta =$ electric power output corrected for rotational losses

$P_m =$ amplitude for the power angle curve

$\delta =$ rotor angle with respect to a synchronously rotating reference

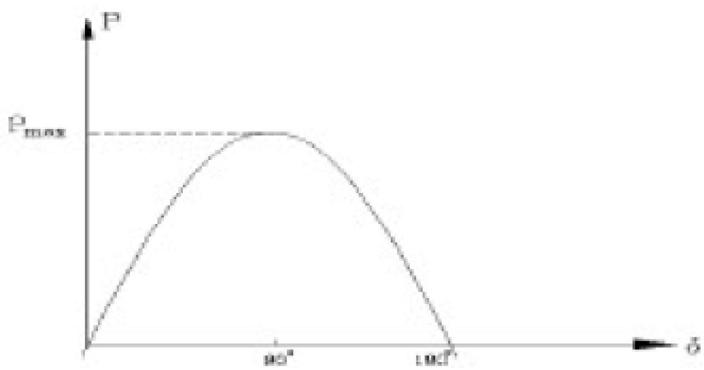


Fig.2.4. Power-angle curve of the system

2.5 EQUAL AREA CRITERION

- For the total area to be zero, the positive part must equal the negative part. (A1=A2)
- $\int_{\partial_o}^{\partial_{c1}} P_{acc}\, d\partial = A1\ (Positive\ Area)$ (2.8)
- $\int_{\partial_{c1}}^{\partial_m} P_{acc}\, d\partial = A1\ (Negative\ Area)$ (2.9)

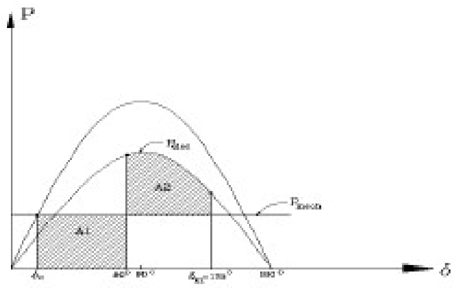


Fig.2.5. Condition showing equal area criterion

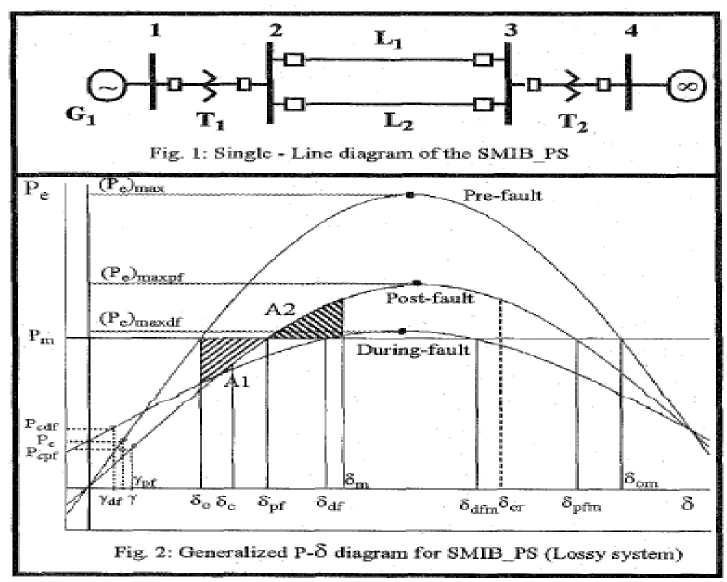


Fig. 2.6. Condition showing fault in the transmission line

and its effects on the swing equation.

Where, $A_1 =$ Area of acceleration

$A_2 =$ Area of deceleration

If the area of acceleration is larger than the area of deceleration, i.e., $A_1 > A_2$. The generator load angle will then cross the point δ_m, beyond which the electrical power will be less than the mechanical power forcing the accelerating power to be positive. The generator will therefore start accelerating before is slows down completely and will eventually become unstable. If, on the other hand, $A_1 < A_2$, i.e., the decelerating area is larger than the accelerating area, the machine will decelerate completely before accelerating again. The rotor inertia will force the subsequent acceleration and deceleration areas to be smaller than the first ones and the machine will eventually attain the steady state. If the two areas are equal, i.e., $A_1 = A_2$, then the accelerating area is equal to decelerating area and this is defines the ***boundary of the stability limit.***

Chapter 3

CONTROL STRATEGIES APPLIED IN TRANSIENT STABILIY ANALYSIS

3.1 INTRODUCTION

The developing of assessment tools for transient stability analysis of electrical power systems has challenged engineers for several decades. The main available tool for transient stability analysis is the step-by-step methodology which integrates numerically the differential equations describing the dynamical behavior of power systems. These assessment tools have significantly improved into the last three decades. Although these methods have some limitations concerning the consideration of more detailed generator models, they have shown to be suitable for fast transient stability assessment. Among the direct methods, the Lyapunov's ideas associated to the LaSalle's Invariance Principle have been used to study the stability of power systems. These methods have the main advantage that information about stability and attraction area can be obtained without solving the differential equations. For that purpose, an auxiliary function, called Lyapunov function, is supposed to exist.

In the direct methods, the stability analysis is divided into two steps. First of all an estimate of the attraction area of the post –fault system is obtained. In the second step, the fault-on trajectory is numerically obtained and it is verified, at the clearing time, if the fault-on trajectory is contained into the attraction area estimate. In the affirmative situation, the system is stable; otherwise no information can be obtained.

Unfortunately, direct methods have the disadvantage that they are not yet suitable for dealing with detailed generators models. In fact, this disadvantage is intimately related to the problem of finding a Lyapunov function when these models are taken into consideration. On the other hand, although the step-by-step programs do not impose any limitation on modeling, they have the disadvantage of being computationally costly. Based on this observation, one cannot say that one method is better than the other. Instead of that, one can claim that they complement each other. Hybrid methods have been successfully used in order to take advantages of both methods in contingency analysis.

In spite of the advances which have occurred mainly in the last two decades, both tools, the step-by-step method and the direct methods, can analyze only one contingency at a time. Then for analyzing the system at a large range of possible situations, a very high number of contingencies and different operating points have to be simulated. Indeed no uncertainties are considered in the parameter determination. As consequence there is no absolute certainty that the stability of the system will be guaranteed for all operating conditions.

We considered the LaSalle's Invariance Principle to give support for the proposal of a transient stability analysis of power systems which is robust with respect to post-fault parameter uncertainties. The proposed methodology obtains an estimate of the attraction area of the post-fault system which is independent of the parameters and is contained into the real attraction area.

The advantages of considering uncertainties in the analysis can be explored in two ways. First of all, when uncertainties are taken into consideration, a selected contingency does not represent an unique situation but a set of situations which are similar to it. Therefore, a less number of contingencies will be probably enough to cover a selected range of situations. The second way of exploring uncertainties is that these uncertainties could be chosen in such a way that similar selected contingencies could belong to the same set of uncertainty parameters. With this choice, a robust estimate of the critical clearing time could be obtained, at same time, for all these contingencies saving a significant computational effort. It is clear from these considerations that contingency analysis could be a promising application for the proposed methodology.

3.1.1 THEORY BEHIND EQUAL AREA CRITERIA

The equal area criterion was the first direct method proposed in the literature to study the transient stability of one-machine-infinite-bus systems. What is behind this criteria and which guarantees the stability of the system are, in reality, the Lyapunov's ideas associated to the LaSalle's Invariance Principle. This section starts with a brief review of the LaSalle's Invariance Principle.

Consider the following autonomous differential equation:

$$\dot{x} = f(x) \qquad (1)$$

Theorem II.1: Let $V : R^n \rightarrow R, f : R^n \rightarrow R^n$ be C^1 functions. Let L > 0 be a constant such that $\Omega_L = \{ x \in R^n : V(x) < L \}$ is bounded. Suppose that $\dot{V}(x) \leq 0$ for every $x \in \Omega_L$ and define $E := \{x \in \Omega_L: \dot{V}(x) = 0\}$. Let B be the largest invariant set contained in E. Then every solution of (1) starting in Ω_L converges to B as t→∞.

This theorem was first proposed and proved b LaSalle in 1960. The function V in the theorem II.1 is the so called Lyapunov function.

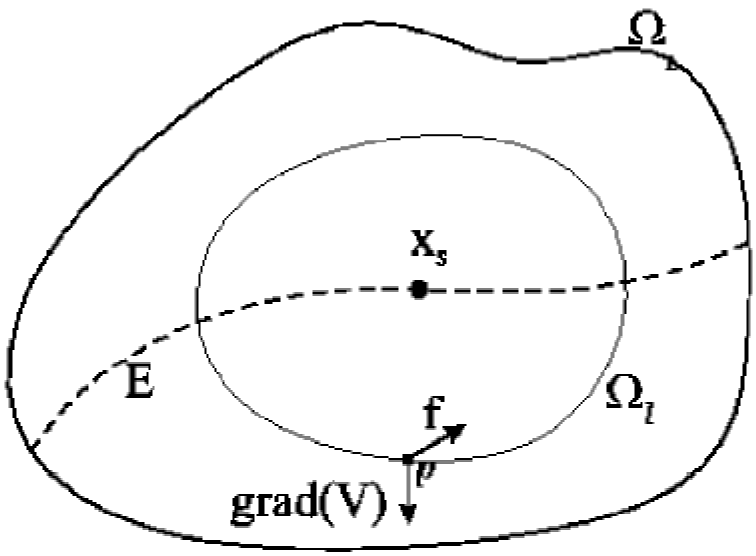


Fig.3.1. Geometric interpretation of the LaSalle's Invariance Principle

It is interesting to interpret geometrically the previous theorem. For that purpose, consider Figure 3.1 which shows a simple application of the LaSalle's theorem. As required by Theorem II.1, Ω_L is a bounded set. The dashed line represents the set where p = 0. Suppose that the largest invariant set contained into E is composed only by the stable equilibrium point x_s. Consider now the level curve $\Omega_l := \{x \epsilon \Omega_L: V(x) = l < L\}$ and let p be a point lying on this curve. As, into the set, Ω_L the derivative of V is less than or equal to zero, one obtains, by the chain rule, the following inequality:

$$\dot{V} = < grad(V), \dot{x} > = < grad(V), f > \leq 0$$

In particular, this inequality is true for the point p. It shows that the inner product between the gradient vector, which is perpendicular to the level curves, and the acceleration vector f, which is tangent to the orbits, is less than or equal to zero. This means that the angle between these vectors is bigger than or equal to 90° as shown in Figure 1. This relation exists for every point of the level curve l of the function V, thus the solutions are entering into the set Ω_l. This conclusion is true for all level curves intoΩ_L, then every solution starting into Ω_L will converge to the stable equilibrium pointx_s.

Remark I.1: Theorem II.1 supposes that the set $\Omega_L = \{ x \in R^n : V(x) < L \}$ is bounded. In fact, if only a connected component of Ω_L is bounded, and then the theorem is true for this component. This conclusion follows from the fact that solutions starting into a connected component cannot leave this component. Let us apply this principle to study the stability of a single-machine-infinite-bus-system whose unifilar diagram is shown in Figure 3.2.

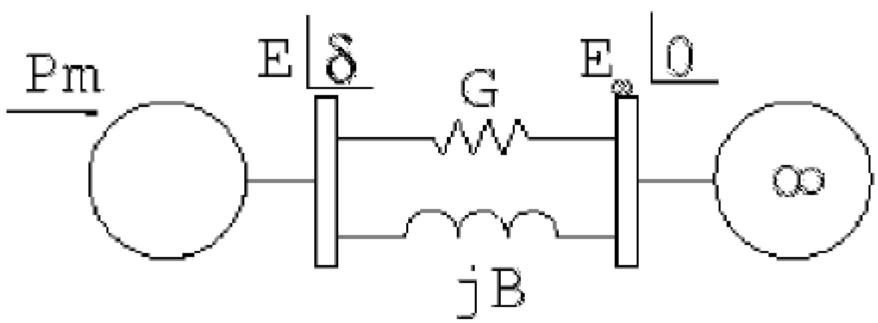


Fig.3.2. One-Machine-Infinite-Bus System

Modeling the generator as a constant electromotive force behind the transient reactance, this system can be described by the following pair of differential equations:

$$\dot{\delta} = \omega$$

$$M\dot{\omega} = P_m - P_e(\delta) - T\omega$$

Where $P_e(\delta) = E^2G$-$EE_\infty B sin\delta - EE_\infty G cos\delta$, δ and ω are respectively the generator rotor angle and the generator frequency deviation with respect to the synchronous frequency, P_m, is the input mechanical power, E is the electromotive force magnitude, E_∞ is the magnitude of the voltage at the infinite bus, T is the damping coefficient and $G + jB$ is the admittance of the equivalent transmission line.

This system has an energy-like Lyapunov function given by:

$$V(\delta,\omega) := \frac{M}{2}\,\omega^2 - P_m\delta + E^2G\,\delta + EE_\infty B\cos\delta - EE_\infty G\sin\delta + \alpha$$

Where α is an arbitrary constant. This energy function can be physically interpreted as a sum of the kinetic energy V_k and the potential energy V_p, that is, $V(\delta,\omega) = V_k(\omega) + V_p(\delta)$, where

$$V_k(\omega) = \frac{M}{2}\,\omega^2$$

$$V_p(\delta) = -P_m\delta + E^2G\,\delta + EE_\infty B\cos\delta - EE_\infty G\sin\delta + \alpha$$

It is easy to show that the derivative of V is given by

$$\dot{V} = -T\omega^2$$

Which is a negative semi-definite function. Therefore the function V satisfies the hypothesis of the LaSalle's Invariance Principle.

In order to estimate the attraction area of the post-fault equilibrium point, the number L must be found such that the hypothesis of Theorem II.1 are satisfied, that is, the connected component of the set Ω_L which contains the stable equilibrium point of interest must be bounded and the unique invariant set contained into E must be the post-fault stable equilibrium point of interest. Since as higher the number L is the greater is the attraction estimate, it is important to choose the highest number L such that the hypothesis of Theorem II.1 is satisfied. Let us see these details in the next example.

Example II.1: Consider the system of one-machine versus infinite bus system of Figure 2 with the following parameters: P_m= 1.0,, M = 0.05, T = 0.03, E = 1.0, E_∞ = 1.0, G = 0.1, B = -2. Suppose a solid short-circuit occurs at the generator terminal bus and this short-circuit is eliminated such that the post-fault parameters are equal to the parameters of the pre-fault system.

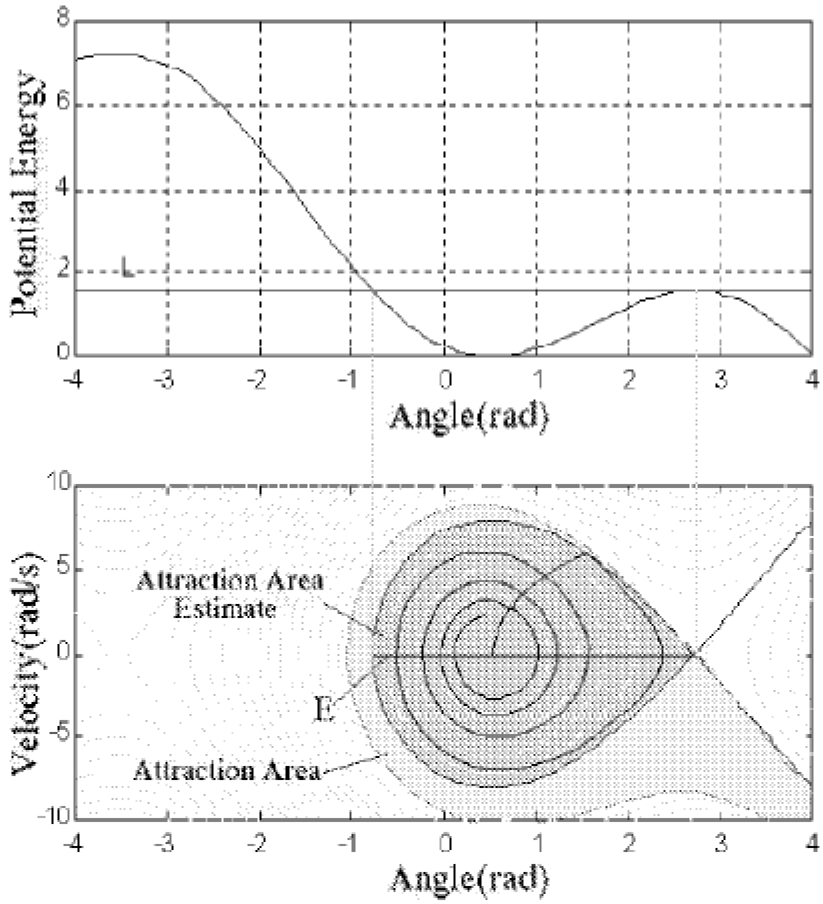


Fig.3.3. Attraction Area Estimate of a OMIB System

Figure 3.3 shows the potential energy V, as a function of the angle δ and the level curves of the function V are depicted in yellow. Observing the level curves of V, it is easy to realize that the maximum value of L which satisfies the requirements of the theorem coincides with the value of the function V evaluated at the unstable equilibrium point located in the right side of the post-fault stable equilibrium point. In this example L = 1.586 (the number L is usually called, in the literature, critical energy V_{cr}). For this choice of L the connected component of the set $\Omega_L = \{(\delta, \omega) \in R^2 : V(\delta, \omega) < 1.586\}$ containing the post-fault equilibrium point is indicated in Figure 3 by the dark grey region. The level curve V = 1.586 is depicted in blue. In this case, the set E is the line segment indicated in blue and the set B is constituted only by the post-fault stable equilibrium point. With these choices of V and L, one can use the LaSalle's Invariance

Principle to show that every solution starting into Ω_L tends to the post-fault stable equilibrium point as time tends to infinity and therefore the set Ω_L is an estimate of the attraction area. This estimate is contained into the real attraction area which is indicated in the figure by the light grey region. The green curve shows the boundary of such attraction area.

In order to estimate the critical clearing time, the differential equations of the fault system are numerically integrated until the total energy of the system is equal to L. The instant in which such equality occurs is the instant in which the fault trajectory leaves the attraction area estimate. This time will be an estimate of the critical clearing time. In this example, the critical clearing time estimate belongs to the interval (0.327; 0.328s) while the real critical clearing time is contained in the interval (0.337; 0.338s). Figure 3 shows the trajectory of the system when the fault is cleared at 0.327s.

3.1.2 ROBUST EQUAL AREA CRITERIA

Here a robust version of the equal area criteria is proposed. While the conventional equal area criteria are based on the LaSalle's Invariance Principle, the robust version, which is proposed in this paper, is based on a Uniform or Robust Version of the Invariance Principle. Consider the following autonomous system:

$$\dot{x} = f(x, \lambda) \qquad (2)$$

Where $\lambda \in \wedge \subset R^m$ is a parameter vector of this system and $x \in R^m$.

Theorem III.1: (**Uniform Invariance Principle**) suppose $f : R^n \text{x} \wedge \longrightarrow R^n$ and $V: R^n \text{x} \wedge \longrightarrow R$ are C^1 functions and $a, b, c : R^n \longrightarrow R$ are continuous functions. Assume that for any $(x, \lambda) \in R^n \text{ x } \wedge$, one has:

$$a(x) \leq V(x, \lambda) \leq b(x), \qquad -\dot{V}(x, \lambda) \geq c(x)$$

For $L > 0$ let $A_L := \{x \in R^n : a(x) < L\}$. Assume that A_L is non empty and bounded.
Consider the sets

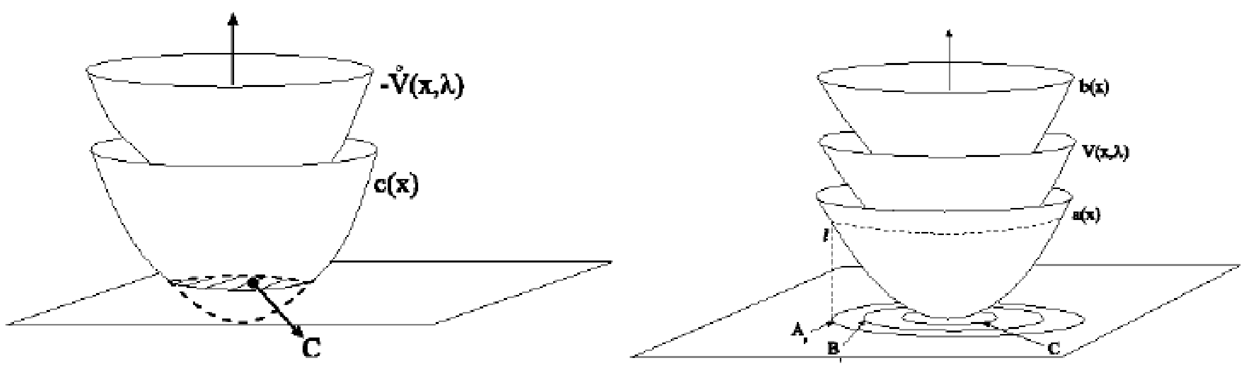
$$B_L := \{x \in R^n : b(x) < L\}, C := \{x \in R^n : c(x) < 0\}$$
$$and\ E_L := \{x \in A_L : c(x) = 0\}$$

Suppose now that $sup_{x\in C}\, b(x) \le l \le L$ and define the sets
$A_l \coloneqq \{x \in R^n\colon a(x) \le l\} and$ B_l:={ $x \in R^n\colon a(x) \le l\}$.

If λ is a fixed parameter in $\wedge$ and all the previous conditions are satisfied then for $x_0 \in \mathrm{B}_L$ the solution $\varphi(t, x_0, \lambda)$ are defined in [0, ∞) and the following holds:

I) If $x_0 \in \mathrm{B}_l$ then $\varphi(t, x_0, \lambda) \in A_l$, for t≥0 and $\varphi(t, x_0, \lambda)$ tends to the largest invariant set of (2) contained in A_l , as t⟶∞.

II) If $x_0 \in \mathrm{B}_L - \mathrm{B}_l$ then $\varphi(t, x_0, \lambda)$ tends to the largest invariant set of (2) contained in $A_l \cup E_L$.



(a) Derivative of the Lyapunov Function (b) Lyapunov Function

Fig.3.4. Functions a, b, e, c of theorem III.1

Note that the uniformity is guaranteed by the existence of the functions a, b and c which are independent of the parameters. Figure 3.4 shows the relation between these functions and the estimates which are obtained with the theorem.

The set C contains the set where $\dot{V}$ is positive independently of the parameter $x \in \wedge$. As consequence, $l = sup_{x\in C}\, b(x) \ge sup_{\{(x,\lambda):\dot{V}>0\}}.V(x, \lambda)$. Then, the level curve l of the function a is used to obtain an estimate of the attractor.

Figure 5 illustrates the application of the Uniform Invariance Principle. Note that $\mathrm{B}_l \subset A_l$ and $\mathrm{B}_L \subset A_L$. The invariance notion in this case is a little bit different. The set B_L is not positively invariant with respect to (2), however one can guarantee that every solution starting into B_L does not leave the set A_L. This is the case of the solutions starting at $x_1$and x_3 in Figure

5. Nothing can be said about solutions starting in A_L - B_L. For example, the solution starting at x_2 goes away from the set A_L.

Every solution starting into B_L. Tends to the largest invariant set contained into A_l U E_L. If a solution enters in B_l, then one can guarantee that this solution will never leave the set A_l > B_l. This is the case of the solution starting at x_3.

The set A_l is an attractor estimate and B_L is an attraction area estimate, that is, A_l contains the attractor and B_L is contained into the attraction area independently of the system parameters.

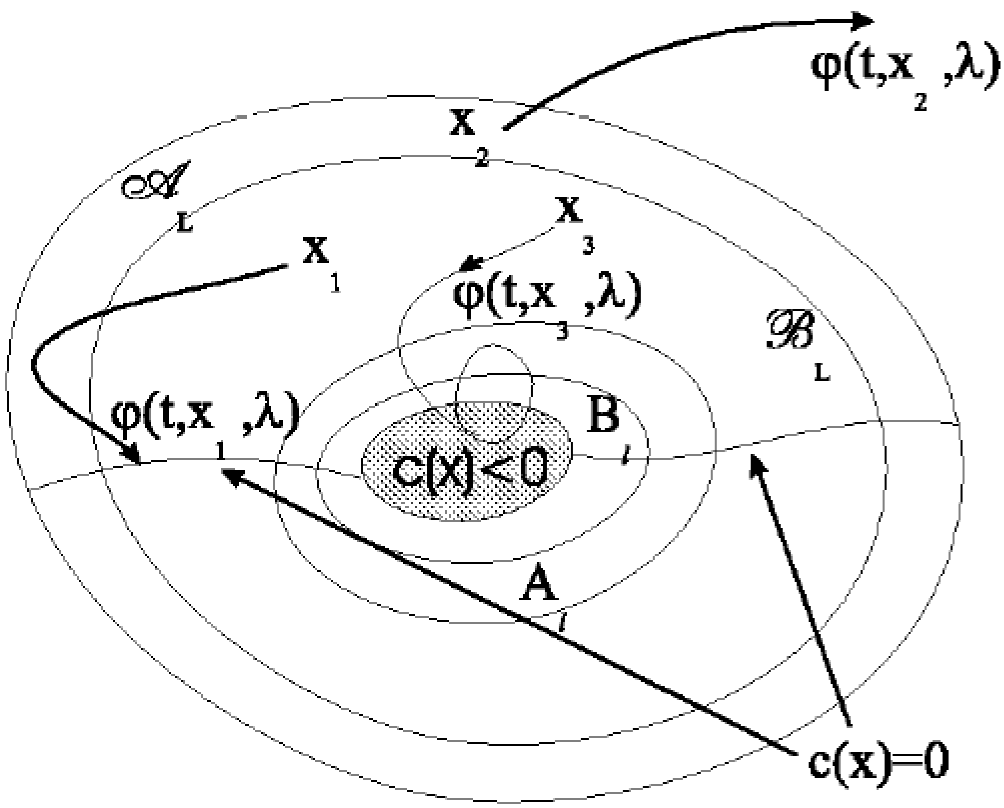


Fig.3.5. Geometric Interpretation of the Uniform Invariance Principle

Let us apply this theorem to study the stability of a single-machine-infinite-bus system considering uncertainties in the post-fault parameters. Suppose that M, P_m, T, E, E_∞ are constants and that there exist uncertainties in the following post-fault parameters:

$$B_{min} \leq B \leq B_{max} \quad G_{min} \leq G \leq G_{max}$$

Define $\lambda = (B, G) and\ \Lambda = \{(B, G) \epsilon R^2 : B_{min} \leq B \leq B_{max}, G_{min} \leq G \leq G_{max}\}$. Consider the same function V used in the previous section but depending on the parameters, that is, $V(\delta, \omega, \lambda) := V_k(\omega) + V_p(\delta, \lambda)$ where

$V_k(\omega) := \frac{M}{2}\omega^2$

$V_p(\delta, \lambda) :=$ $- P_m\delta + E^2G\ \delta + EE_\infty B cos\delta - EE_\infty G sin\delta + \alpha$

And α is an arbitrary constant.

Functions $a\ and\ b$ of Theorem III.1 can be easily chosen as being :

$b(\delta, \omega) \coloneqq b_k(\omega) + b_p(\delta)$

$a(\delta, \omega) \coloneqq a_k(\omega) + a_p(\delta)$

where

$$\begin{aligned} b_k(\omega) &= \frac{M}{2}\omega^2 \\ b_p(\delta) &= - P_m\delta + \{E^2G_{max}\ \delta\ if\ \delta > 0;\ E^2G_{min}\delta\ if\ \delta \leq 0\} \\ &\quad +\{ EE_\infty B_{max} cos\delta\ if cos\ \delta > 0;\ EE_\infty B_{min} cos\delta\ if\ cos\delta \leq 0\} \\ &\quad -\{ EE_\infty G_{min} sin\delta\ if sin\delta > 0;\ EE_\infty G_{max} sin\delta\ if\ sin\delta \leq 0\} \\ &\quad +\alpha \end{aligned}$$

$$\begin{aligned} a_k(\omega) &= \frac{M}{2}\omega^2 \\ a_p(\delta) &= - P_m\delta + \{E^2G_{min}\ \delta\ if\ \delta > 0;\ E^2G_{max}\delta\ if\ \delta \leq 0\} \\ &\quad +\{ EE_\infty B_{min} cos\delta\ if cos\ \delta > 0;\ EE_\infty B_{max} cos\delta\ if\ cos\delta \leq 0\} \\ &\quad -\{ EE_\infty G_{max} sin\delta\ if sin\delta > 0;\ EE_\infty G_{min} sin\delta\ if\ sin\delta \leq 0\} \\ &\quad +\alpha \end{aligned}$$

3.2 TRANSIENT STABILITY ANALYSIS: A COMPUTING CHALLENGE

Transient stability analysis is concerned with the electrical distribution network, electrical loads and the electro-mechanical equations of motion of the interconnected generators. Traditionally, power system transient stability analysis has been performed off-line to understand the system's ability to withstand specific disturbances and the system's response characteristics, such as damping of generator oscillations, as a system returns to normal operation. To date the computational complexity of transient stability problems have kept those from being run in real time to support the decision making at the time of a disturbance. If the transient stability program could run in a faster than real time then power system control room operators could be provided with a detailed view of the scope of cascading failures. This view of the unfolding situation could assist an operator in understanding the magnitude of the problem and its ramifications so that proactive measures could be taken to limit the extent of the incident. Faster transient stability simulation implementations may significantly improve power system reliability which in turn will directly or indirectly affect:

- Electrical utility company profits
- Environmental impact
- Customer satisfaction

In addition to real time analysis, there are other areas where transient stability could become an integral part of daily power system operations:

- System restoration analysis
- Economic/environmental dispatch
- Expansion planning

Real time or faster than real time transient stability could also be a significant benefit to an operator when a power system is being restored after an outage. Incorrect decisions concerning the order to switch loads and generators capacity back on-line could cause recurrences of cascading system failures or even physical damage to generators, transformers and power lines.

It will be shown that computational requirements are a significant problem with transient stability simulations. The scope of real time or faster than real time analysis places this application in the category of being a grand computing challenge that could benefit from future teraflop (trillion floating point operations per second) supercomputers.

3.3 AUTOMATIC GENERATION CONTROL STRATEGIES IN POWER SYSTEMS:

The successful operation of interconnected power systems require matching of total generation with total load demand and associated system losses. With time, the operating point of a power system changes, and hence, these systems may experience deviations in nominal system frequency and scheduled power exchanges to other areas, which may yield undesirable effects.

3.3.1Overview:

The first attempt in the area of AGC schemes has been to control the frequency of power system via the flywheel governor of the synchronous machine. This technique was subsequently found to be insufficient, and a supplementary control was included to the governor with the help of a signal directly proportional to the frequency deviation plus its integral. These works based on tie line bias control strategy.

Control techniques

The pioneering works by a number of a control engineers namely Bode, Nyquist and black has established links between the frequency response of a control system and its closed loop transient performance in the time domain. The investigations carried out using classical control approaches reveal that it will result in relatively large overshoots and transient frequency deviation. The AGC regulator design techniques using modern optimal control theory enable the power engineers to design an optimal control system with respect to given performance criterion. The feasibility of an optimal AGC scheme requires the availability of al state variables for feedback. However, these efforts seem unrealistic , since it is difficult to achieve this. The problem is to reconstruct the unavailable states from the available outputs and controls using a observer. Exploiting the fact that the nonlinearity of the power system model ,namely, tie-line power flow, is measurable , the observer has been designed to give zero asymptotic error, even for the nonlinear model.

3.3.2 CONTROL STRATEGIES:

Many control strategies have been proposed on the basis of class disturbances. A feedback and loop gain to eliminate the disturbance and a different feedback form can be used to develop optimal controllers for an electrical energy system. The decentralized AGC concept appeared I the power system control scenario to deal with such problems very effectively. A class of systematic distributed control design methods based on:

- Distributed implementations of centralized control systems
- Model reduction of dynamical systems
- Modeling of interaction between the subsystems comprising global control system

Excitation control and load characteristics

In most of the AGC studies, it is assumed that there is no interaction between the power/frequency and reactive –power voltage control loops. It may be permissible only when the speed of the excitation systems is much faster. The optimal accommodation of load disturbances could lead to significantly better performance than that of conventional controllers. The disturbance effects in the system can be cancelled completely.

Chapter 4

MODELLING AND SIMULATION OF POWER SYSTEM

4.1 SIMULINK

Simulink is advanced software which is increasingly being used as a basic building block in many areas of research. As such, it holds a great potential in the area of power system example to demonstrate the features and scope of Simulink –based model for transient stability analysis.

The stability of power systems continues to be major concern in system operation. Modern electrical power systems have grown to a large generating units and extra high voltage tie-lines, etc. The transient stability is a function of both operating conditions and disturbances. Thus the analysis of transient stability is complicated. Simulink is an interactive environment for modeling, analyzing and simulating a wide variety of dynamic systems. The key features of Simulink are:

- Interactive simulations with live display;
- A comprehensive block library for creating linear, non linear, discrete or hybrid multi-input/output systems;
- Seven integration methods for fixed step, variable step and stiff systems;
- Unlimited hierarchical model structure;
- Scalar and vector connections;
- Mask facility for creating custom blocks and block libraries;

4.2 SYSTEM MODELLING

The complete system has been illustrated in terms of Simulink blocks in a single integral model. One of the most important features of Simulink is it being interactive, which is proved by display of signal at each and every terminal. A parameter within any block can be controlled from a MATLAB command line or through an m–file program. This is used as in transient stability study as the power system configurations differ before, after and during the fault. Loading conditions and control measures can also be implemented accordingly.

Classical system model

The complete 3- generator system in the figure below has been simulated as a single integral model in Simulink. The mathematical model given above gives the transfer function of different blocks. Fig. 2 shows the complete block diagram of classical system representation for transient stability study. The subsystems 1, 2 and 3 in Fig. 2 are meant to calculate the value of electrical power output of generator 1. Similarly other subsystems can be modelled.

Mathematical modeling

Once the **Y** matrix for each network condition (pre-fault, during and after fault) is calculated, we can eliminate all the nodes except for the internal generator nodes and obtain the **Y** matrix for the reduced network. The reduction can be achieved by matrix operation with the fact in mind that all the nodes have zero injection currents except for the internal generator nodes. In a power system with *n* generators, the nodal equation can be written as:

$$\begin{bmatrix} I_n \\ 0 \end{bmatrix} = \begin{bmatrix} Y_{nn} & Y_{nr} \\ Y_{rn} & Y_{rr} \end{bmatrix} \begin{bmatrix} V_n \\ V_r \end{bmatrix} \tag{4.1}$$

Where subscript *n* used to denote generator nodes and the subscript *r* is used for the remaining nodes.

Expanding eqn (1),

$$I_n = Y_{nn}V_n + Y_{nr}V_r, \quad 0 = Y_{rn}V_n + Y_{rr}V_r$$

From which we eliminate V_r to find

$$I_n = (Y_{nn} - Y_{nr}Y_{rr}^{-1}Y_{rn})V_n \tag{4.2}$$

Thus the desired reduced matrix can be written as follows:

$$Y_r = (Y_{nn} - Y_{nr}Y_{rr}^{-1}Y_n) \tag{4.3}$$

It has dimensions ($n \times n$) where *n* is the number of generators. Note that the network reduction illustrated by eqns (1)–(3) is a convenient analytical technique that can be used only when the loads are treated as constant impedances. For the power system under study, the reduced matrices are calculated. Appendix II gives the resultant matrices before, during and after fault.

The power into the network at node *i*, which is the electrical power output of machine *i*, is given by[12]

$$P_{ei} = E_i^2 G_{ii} + \sum_{\substack{j=1 \\ j\neq 1}}^{n} E_i E_j Y_{ij} \cos(\theta_{ij} - \delta_i + \delta_j) \quad i = 1,2,3,\dots,n \tag{4.4}$$

Where,

$\overline{Y_{ij}} = Y_{ij}\angle\theta_{ij} = G_{ij} + jB_{ij}$

=negative of the transfer admittance between nodes i and j

$\overline{Y_{ii}} = Y_{ii}\angle\theta_{i} = G_{ii} + jB_{ii}$

= driving point admittance of node i

The equation of motion are then given by

$$\frac{2H_i}{W_R}\frac{dw_i}{dt} + D_i w_j = P_{mi} - \left[E_i^2 G_{ij} + \sum_{\substack{j=1 \\ j\neq 1}}^{n} E_i E_j Y_{ij}\cos\left(\theta_{ij} - \delta_i + \delta_j\right)\right] \quad (4.5)$$

and $$\frac{d\delta_i}{dt} = w_i - w_R \quad i = 1,2,\dots,n \quad (4.6)$$

It should be noted that prior to the disturbance (t=0) $P_{mi0} = P_{ei0}$;

Thereby,

$$P_{mi0} = E_i^2 G_{ii0} + \sum_{\substack{j=1 \\ j\neq 1}}^{n} E_i E_j Y_{ij0}\cos\left(\theta_{ij0} - \delta_{i0} + \delta_{j0}\right) \quad (4.7)$$

The subscript 0 is used to indicate the pre-transient conditions.

As the network changes due to switching during the fault, the corresponding values will be used in above equations.

4.3 CASE STUDY OF A THREE-MACHINE NINE-BUS SYSTEM

The same assumptions used for a system of one machine connected to an infinite bus often assume valid for a multimachine system:

1. Mechanical power input is constant.
2. Damping or asynchronous power is negligible.
3. Constant-voltage-behind-transient-reactance model for the synchronous machines is valid.
4. The mechanical rotor angle of a machine coincides with the angle of the voltage behind the transient reactance.
5. Passive impedances represent loads.

This model is useful for stability analysis but is limited to the study of transients for only the “first swing” or for periods on the order of one second.

Assumptions 2 are improved upon somewhat by assuming a linear damping characteristic. A damping torque (or power) D_w is frequently added to the inertia torque (or power) in the swing equation. The damping coefficient D includes the various damping torque coefficients, both mechanical and electrical. This represents turbine damping, generator electrical damping, and the damping effect of electrical loads.

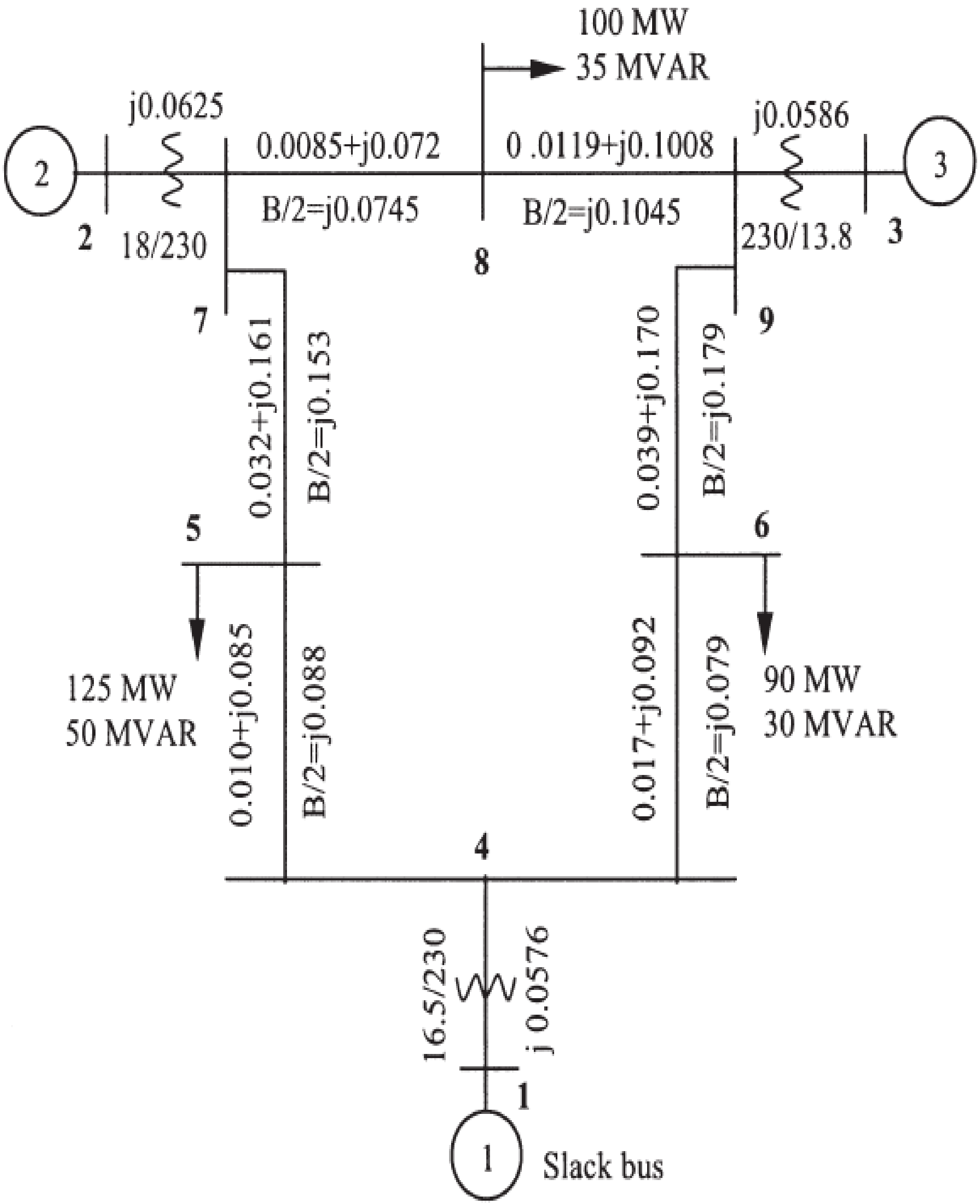


Fig.4.1 3-machine 9-bus system which has to be simulated

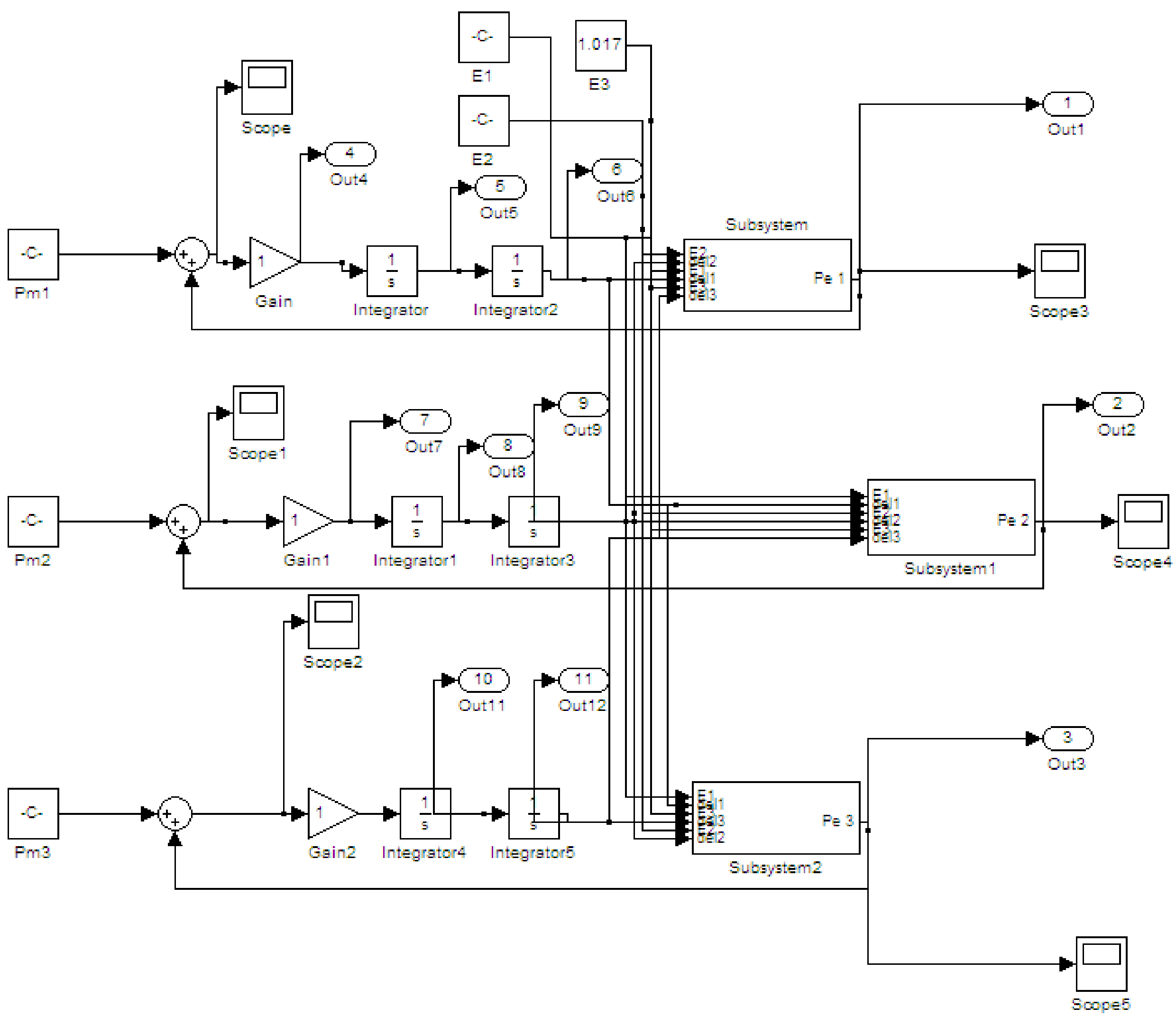


Fig. 4.2 Complete classical system model for transient stability study in Simulink

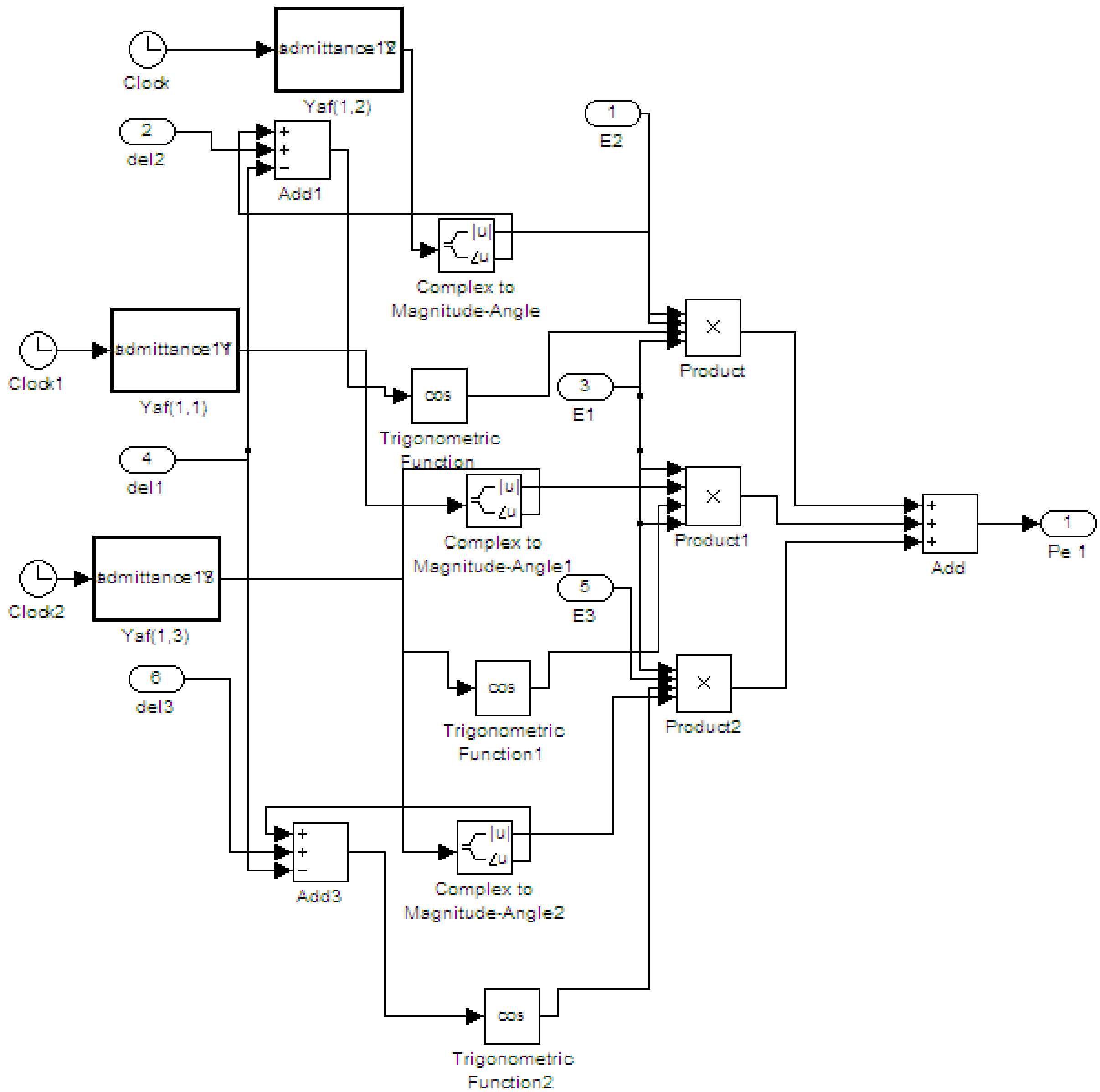


Fig. 4.3 Computation of electrical power output by generator#1(SIMULINK model)

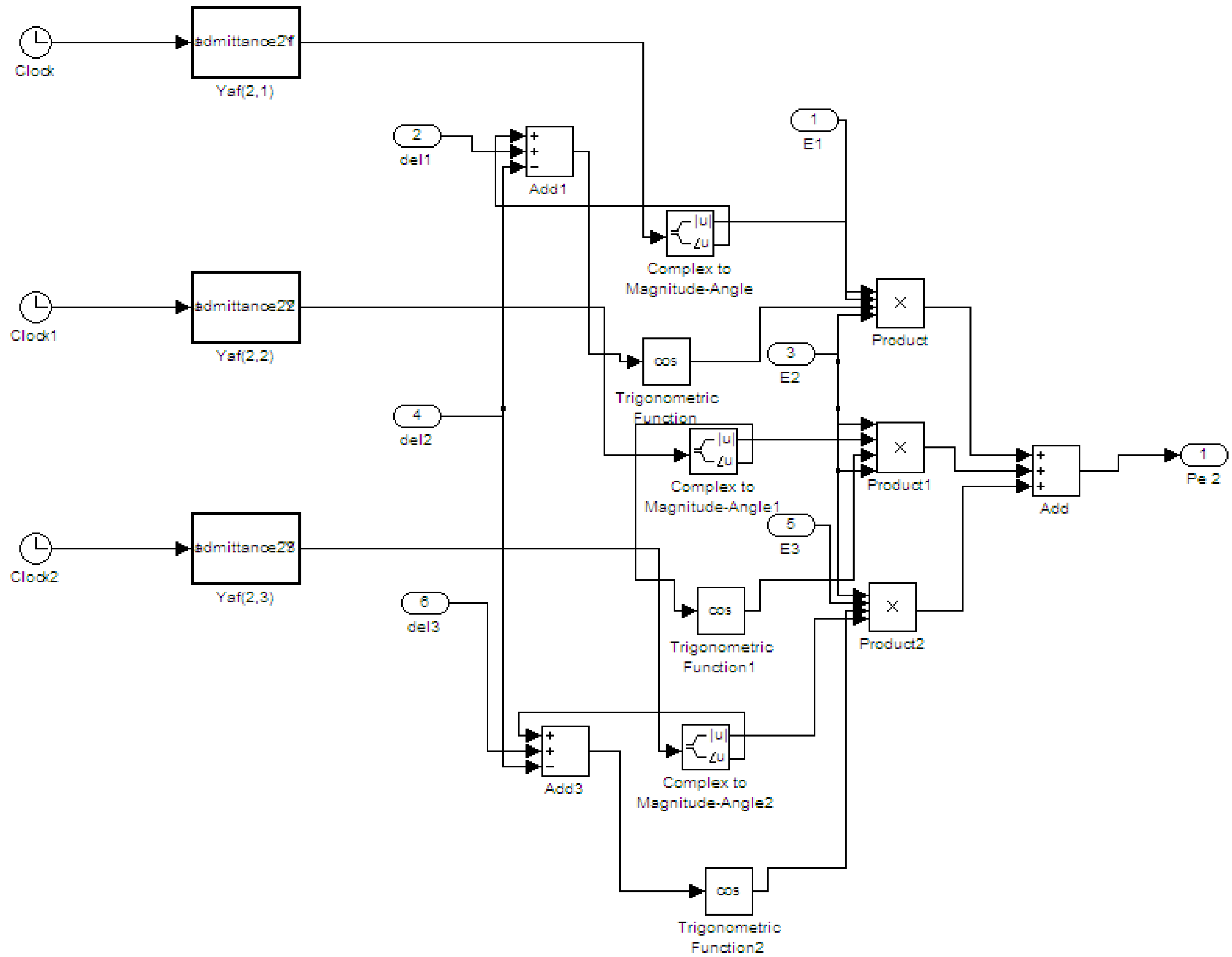


Fig. 4.4 Computation of electrical power output by generator#2(SIMULINK model)

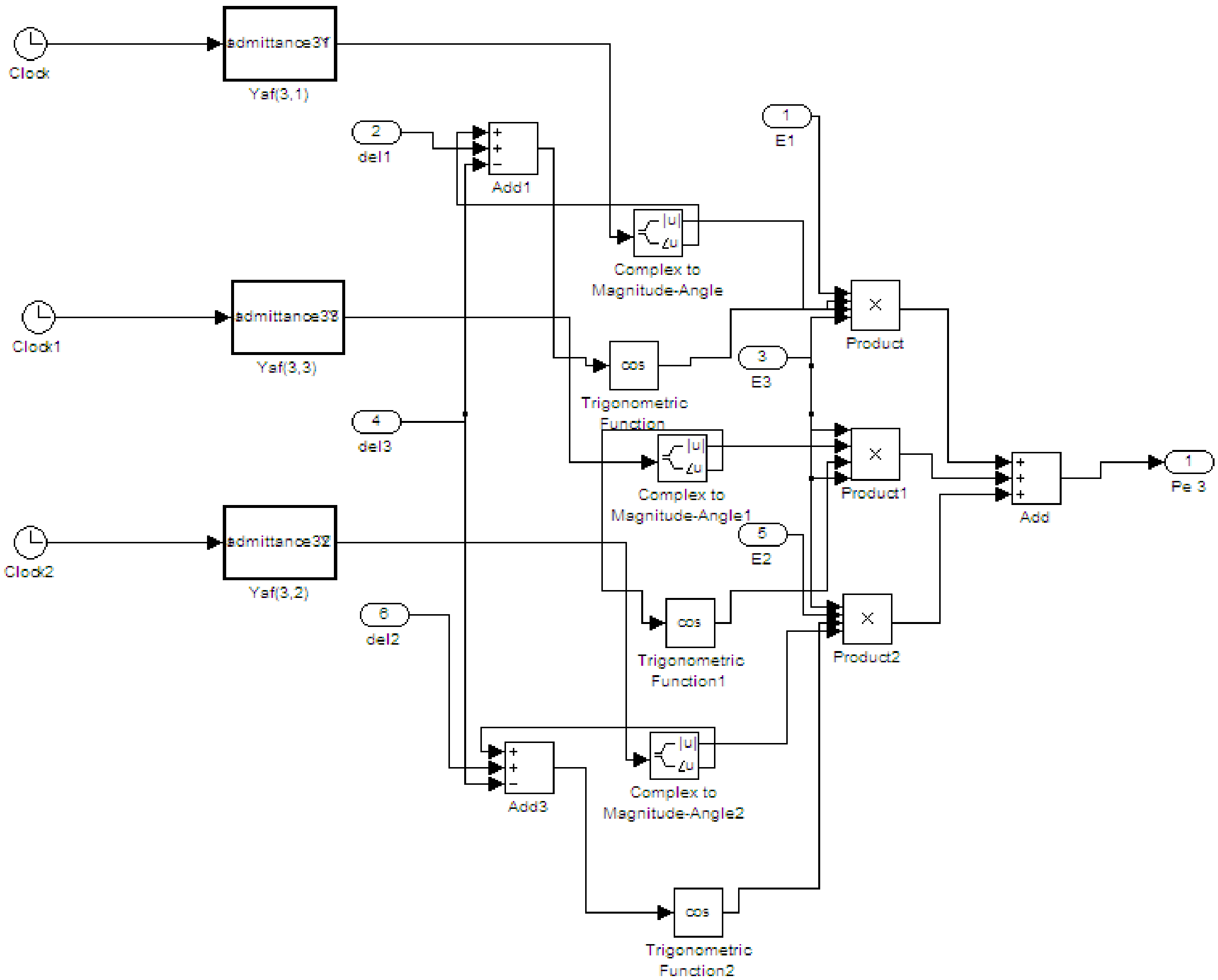


Fig. 4.5 Computation of electrical power output by generator#3(SIMULINK model)

Definition of parameters

- E_x – Generator output voltage of machine#x
- $Y_{af}(x, y)$ - Transfer admittance between nodes x and y.
- P_{mx} - Mechanical power output of generator x.
- P_{ex} - Electrical power output of generator x.

4.4 RESULTS AND DISCUSSIONS

In the above system various cases are there;

Case 1: Pre Fault condition t<5

Case 2: During Fault condition (Fault occurred in line 5-7) t>5 and t<7

Case 3: Post Fault condition (Line 5-7 is removed) t>7

Considering the above cases the behavior of the line is examined here.

The MATLAB simulation result of the power system is shown in the figure given below. The fault occurred during the period between 1 to 1.25 sec. After 1.25 sec the line is removed. The relative variation in rotor angle and the change in angular speed of the rotor is examined. After 1.25 the relative variation in rotor angle and relative change in angular speed starts to damp out. After time 2.25 sec the line is restored.

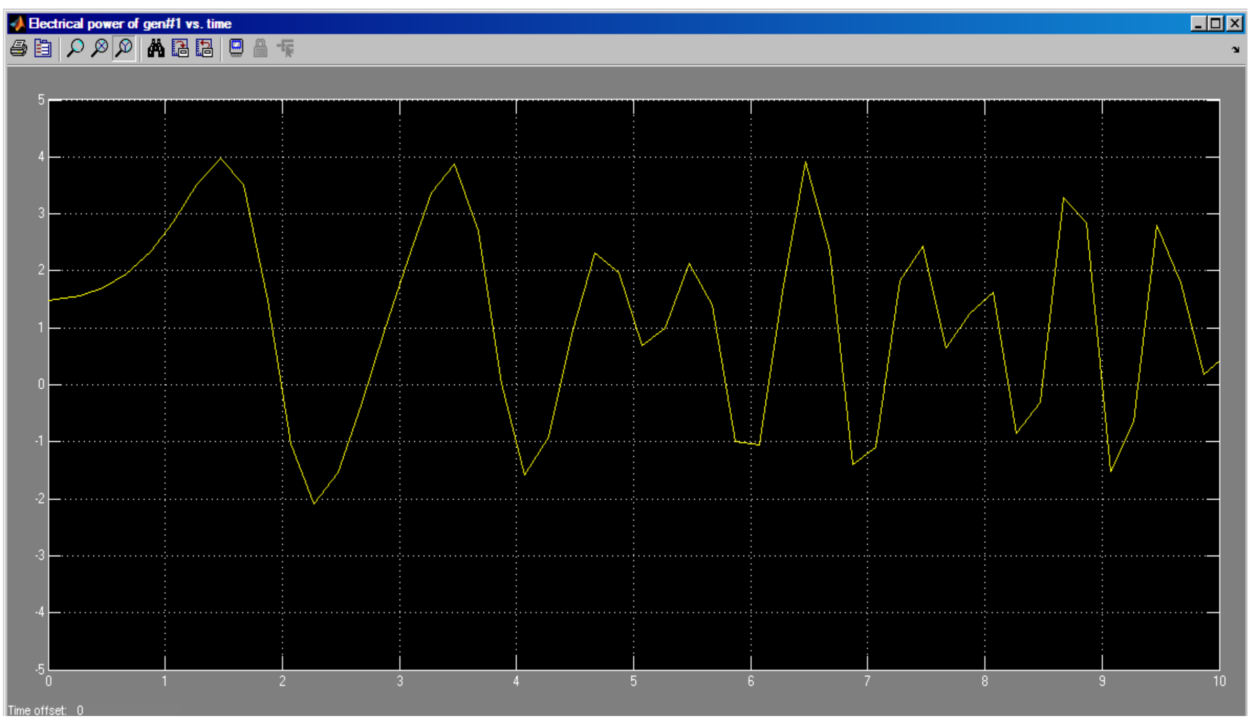


Fig. 4.6 Plot of electrical power of gen#1 vs time

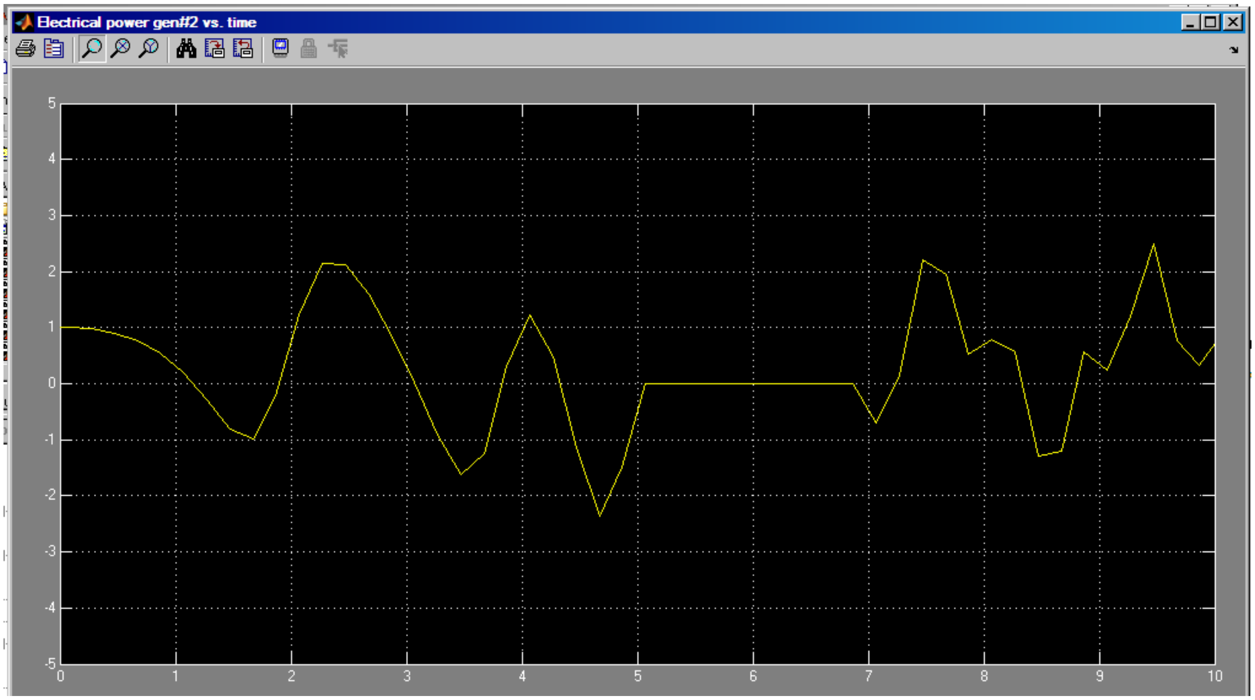


Fig 4.7 Plot of electrical power output of gen#2 vs. time

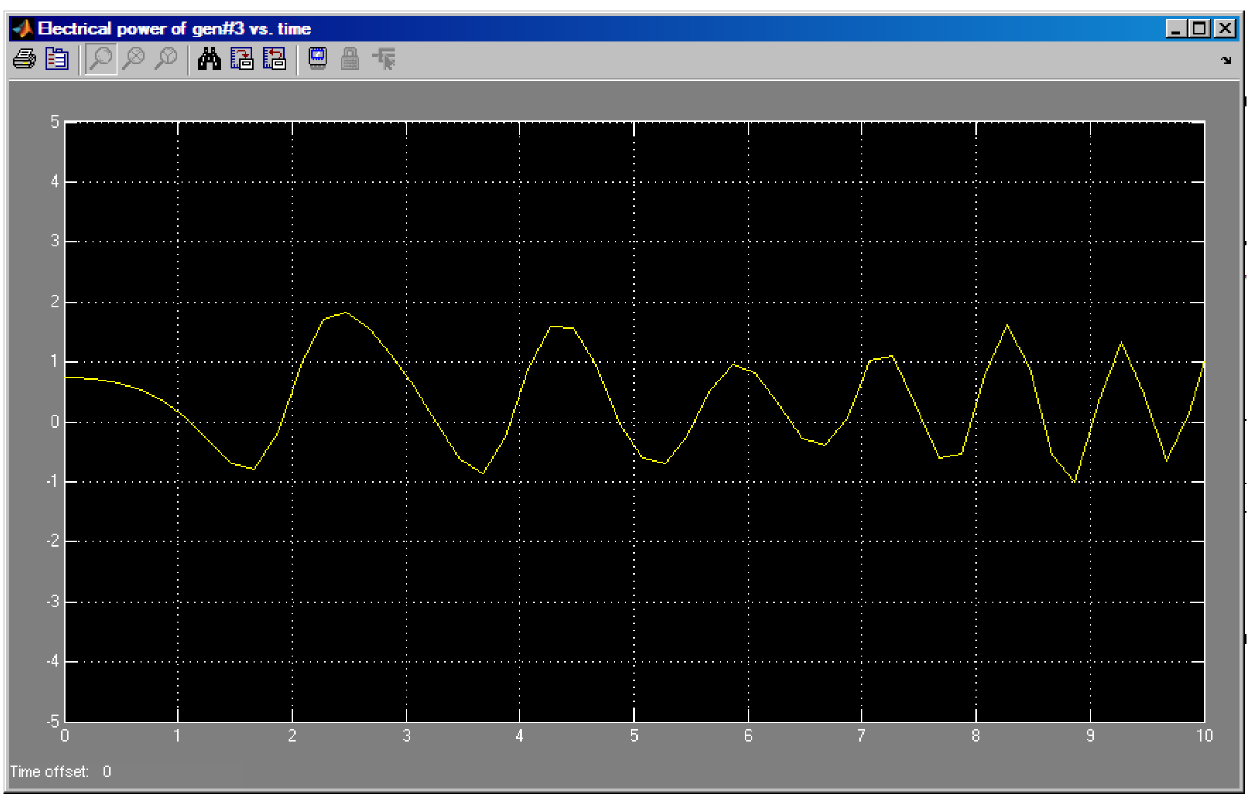


Fig. 4.8 Plot of electrical power output of gen#3 vs time

Chapter 5

CONCLUSIONS AND ASPECTS OF FUTURE WORK

5.1 CONCLUSION

As we had observed that the controlling in the load side is complex. So, we will be controlling generation side. By controlling the generation side the synchronism of the system is always maintained whether the fault is caused by voltage or current. It also helps in maintaining the system efficiency and providing better service to consumer.

5.2 ASPECTS OF FUTURE WORK

To date the computational complexity of transient stability problems have kept them from being run in real-time to support decision making at the time of a disturbance. If a transient stability program could run in real time or faster than real time. Then power system control room operators could be provided with a detailed view of the scope of cascading failure. This view of unfolding situation could assist an operator in understanding the magnitude of the problem and its ramifications so that proactive measure could be taken to limit the extent of the incident. Faster transient stability simulation implementations may significantly improve power system reliability which in turn will directly or indirectly affect.

1. electrical utility company profits
2. environmental impact
3. customer satisfaction

In addition to real time analysis, there are other areas where transient stability analysis could become an integral part of daily power system operations.

1. system restoration analysis
2. economic / environmental dispatch
3. expansion planning

REFERENCES

[1] S. B. GRISCOM, "A Mechanical Analogy of the Problem of Transmission Stability," *Elec. Jour.*, vol. 23, pp. 230-5, May, 1926.

[2] P. KUNDER, “Power system stability and control, EPRI Power system Engineering Series” (Mc Graw-Hill, New York, 1964).

[3] I.J. NAGRATH and D.P.KOTHARI, “Power system Engineering” (Tata Mc Graw-Hill, New York, 1964).

[4] S. B. GRISCOM, "A Mechanical Analogy of the Problem of Transmission Stability," *Elec. Jour.*, vol. 23, pp. 230-5, May, 1996.

[5] R. D. BOOTH and G. C. DAHL, "Power System Stability—a Non-mathematical Review," *Gen. Elec. Rev.*, vol. 33, pp. 677-81, December, 1930; and vol. 34, pp. 131-41, February, 1931.

[6] SHENGLI CHENG, MOHINDAR S. SACHDEV, “Out-of-step protection using the equal area criterion” *University of Saskatchewan Canada* (6-09-2005)

[7] H. SAADAT, “Power System Analysis”, second edition, McGraw-Hill Higher Education, 2002

[8] D. TZIOUVARAS and D. HOU, “Out-of-Step Protection Fundamentals and Advancements,” Proc.30th Annual Western Protective Relay Conference, Spokane, WA, October 21–23, 2003.

[9] VIJAY VITTAL, Harpole professor, department of electrical and computer engineering LOWA STATE UNIVERSITY “Transient stability and control of large scale power systems”, September 4, 2003

[10] Y. DONG and H.R. POTA “Transient stability margin prediction using equal area criterion” February 14, 1998

[11] D.P. KOESTER, S. RANKA, and G.C. FOX School of computer and information science and (NPAC) Syracuse University “Power System Transient Stability- A Grand Computting Challenge” August 31, 1992

[12] IBRAHEEM, PRABHAT KUMAR, and DWARKA P. KOTHARI, *Senior Member, IEEE* “Recent Philosophies of Automatic Generation Control Strategies in Power Systems”

[13] L. Hari, M. L. Kothari, and J. Nanda, “Optimum selection of speed regulation parameters for automatic generation control in discrete mode considering generation rate constraints,” *Proc. Inst. Elect. Eng. C*, vol. 138, no. 5, pp. 401–406, Sep. 1991.

[14] RAMNARAYAN PATEL, T. S. BHATTI and D. P. KOTHARI *Centre for Energy Studies, Indian Institute of Technology, Hauz Khas, New Delhi, India"* MATLAB/Simulink-based transient stability analysis of a multimachine power system" September 1,2003
[15] NEWTON G. BREATAS - Senior Member, IEEE and Luis F.C. Albert0 - Student Member, IEEE "Transient Stability Analysis of Power Systems: Robustness with Respect to Parameter Uncertainties" February 13, 2002.