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TRANSIENT STABILITY ANALYSIS OF POWER SYSTEM USING MATLAB-SIMULINK

SUBJECT CODE: EE755

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CERTIFICATE OF APPROVAL

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-Authors

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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 vigorously growing and extending over vast geographical regions, it is becoming most difficult to maintain synchronism between various parts of the power system. Also, trend to merge existing systems into much larger entities has created further problems. The difficulties increase further when it comes to transient stability phenomenon.

The transient stability of the power system is its ability to regain its normal operating conditions when it is subjected to disturbances for a very short interval. 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. Generally, the fault occurs in the transmission and distribution side rather than at the generation side. Controlling from the former is quite complex, which is why we go for the latter one i.e. generation side.

In our project, we have studied and analysed the basics of load flow studies and have focused on the transient stability analysis of single machine connected to infinite bus, grid connected multi-machine system, during fault and post fault by applying Newton-Raphson method for load flow analysis using MATLAB-SIMULINK. We have also checked the stability under several circumstances like sudden increase in power input, three phase faults at the sending end and at the mid-point of a transmission line. Further, we have calculated the critical clearing time of these faults to maintain synchronism with the power system. Lastly, we have applied Equal Area Criterion to analyse the stability of the system.

Keywords: *Power System Stability, Transient Stability, Critical Clearing Time, Critical Clearing Angle, Power Angle, Equal Area Criterion*

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LIST OF SYMBOLS

D	:	Damping Constant
F_r	:	Rotor Field MMF
M	:	Inertia Constant
P	:	Number of Poles
P_{elec}	:	Output Electrical Power
P_{mech}	:	Input Mechanical Power
T	:	Mechanical Shaft Torque
Δ	:	Power (Rotor) Angle
φ_{air}	:	Air Gap Flux

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LIST OF ABBREVIATIONS

AIEE	:	*American Institute of Electrical Engineers*
ANN	:	*Artificial Neural Network*
BASIC	:	*Beginner's All-purpose Symbolic Instruction Code*
CCT	:	*Critical Clearing Time*
EAC	:	*Equal Area Criterion*
EHV	:	*Extra High Voltage*
FORTRAN	:	*Formula Translation*
GIS	:	*Gas Insulated Switchgear*
HT	:	*High Tension*
HV	:	*High Voltage*
MATLAB	:	*Matrix Laboratory*
MJ	:	*Mega Joule*
MVA	:	*Mega Volt-Ampere*
WTG	:	*Wind Turbine Generator*

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1 INTRODUCTION

1.1 Background

In all power systems, the larger machines are of the synchronous type; these include substantially all the generators and condensers, and a considerable part of the motors. On such systems it is necessary to maintain synchronism; otherwise a standard of service to the consumers will not be achieved. The transient disturbances are caused by the changes in loads, switching operation, and particularly, faults and loss of excitation. Thus, maintenance of synchronism during steady state conditions and regaining of synchronism or equilibrium after a disturbance are of prime importance to the electrical utilities. The term 'stability' can be interpreted as 'maintenance of synchronism'. These two terms are quite frequently used interchangeably.

The present trend is towards interconnection of the power system; resulting into increased length and increased reactance of the system, this presents an acute problem of maintenance of the stability of the system. The term 'power limit' is also sometimes interpreted as 'stability' because to have the maximum utility of the system it should be capable of supplying maximum power without causing instability. Power system stability, in general terms, may be defined as its ability to respond to a disturbance from its normal operation by returning to a condition where the operation is again normal.

The terms 'stability' and 'stability limit' are defined by A.I.E.E. as below:

Stability when used with reference to a power system, is that attribute of the system, or part of the system, which enables it to develop restoring force between the elements thereof, equal to or greater than the disturbing forces so as to restore a state of equilibrium between the elements. A stability limit is the maximum power flow possible through some particular point in the system or the part of the system to which the stability limit refers is operating with stability.

1.2 MATLAB Software

MATLAB, is a registered trademark of Math works, is a high-level programming language which uses matrices as the basic numerical entities (rather than scalars, as in the low-level

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programming languages such as BASIC, FORTAN, PASCAL and C). MATLAB allows us to directly manipulate matrices-such as adding, multiplying, inverting matrices and solving for Eigen values and Eigen vectors of matrices. MATLAB contains a library of many useful functions-both basic functions and specialized mathematical functions with an advanced facility for plotting and displaying the results of computations in various graphical forms. MATLAB software is increasingly being used as a basic program in many areas of research. As such, it also holds great trend in the area of power system. MATLAB has been designed and developed by engineers for engineers to handle the diverse discipline of power systems for a broad spectrum of industries in one integrated package with multiple interface views such as AC and DC networks, cable raceways, ground grid, GIS, panels, arc flash, WTG, protective device coordination/selectivity, and AC and DC control system diagrams. In this paper I have taken a multimachine power system example to demonstrate the features and scope of a MATLAB program for transient stability analysis. A program has been developed which can work as a basic structure for advanced and detailed study.

1.3 Causes of Instability Problems

The major causes to industrial power system instability problems include, but are not limited to:

a. Short-circuits
b. Loss of a tie connection to a utility system
c. Loss of a portion of in-plant co-generation (generator rejection)
d. Starting a motor that is large relative to the system generating capacity
e. Switching operations of lines, capacitors, etc.
f. Impact loading (motors and static loads)
g. A sudden large step change of load or generation

1.4 Consequences of Instability Problems

The consequences of power system instability problems usually are very severe and can range from permanent damage on equipment and shutting down processes, all the way to causing a whole area power outage. Some typical consequences are listed below:

a. Area-wide blackout

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b. Interruption of loads
c. Low-voltage conditions
d. Damage to equipment
e. Relay and protective device malfunctions

1.5 Purpose for Performing Transient Stability Study

Dynamic performance of a power system is significant in the design and operation of the system. The transient stability study determines the machine power angles and speed deviations, system electrical frequency, real and reactive power flows of the machines, power flows of lines and transformers, as well as the voltage levels of the buses in the system. These system conditions provide indications for system stability assessments. The results are displayed on the one-line diagram, and also can be printed or plotted. For transient stability studies, you should model particular groups of machines in the system, which are known to have important influences on the system operation. The total simulation time for each study case should be sufficiently long to obtain a definite stability conclusion.

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2 LITERATURE REVIEW

2.1 Power System Stability

Stability of a power system is its ability to return to normal or stable operating conditions after having been subjected to some form of disturbance. Conversely, instability means a condition denoting loss of synchronism or falling out of step. Furthermore, stability is the tendency of a power system to develop restoring forces equal to or greater than the disturbing forces in order to maintain the state of equilibrium. The system is said to remain stable (to stay in synchronism), if the forces tending to hold machines in synchronism with one another are sufficient to overcome the disturbing forces.

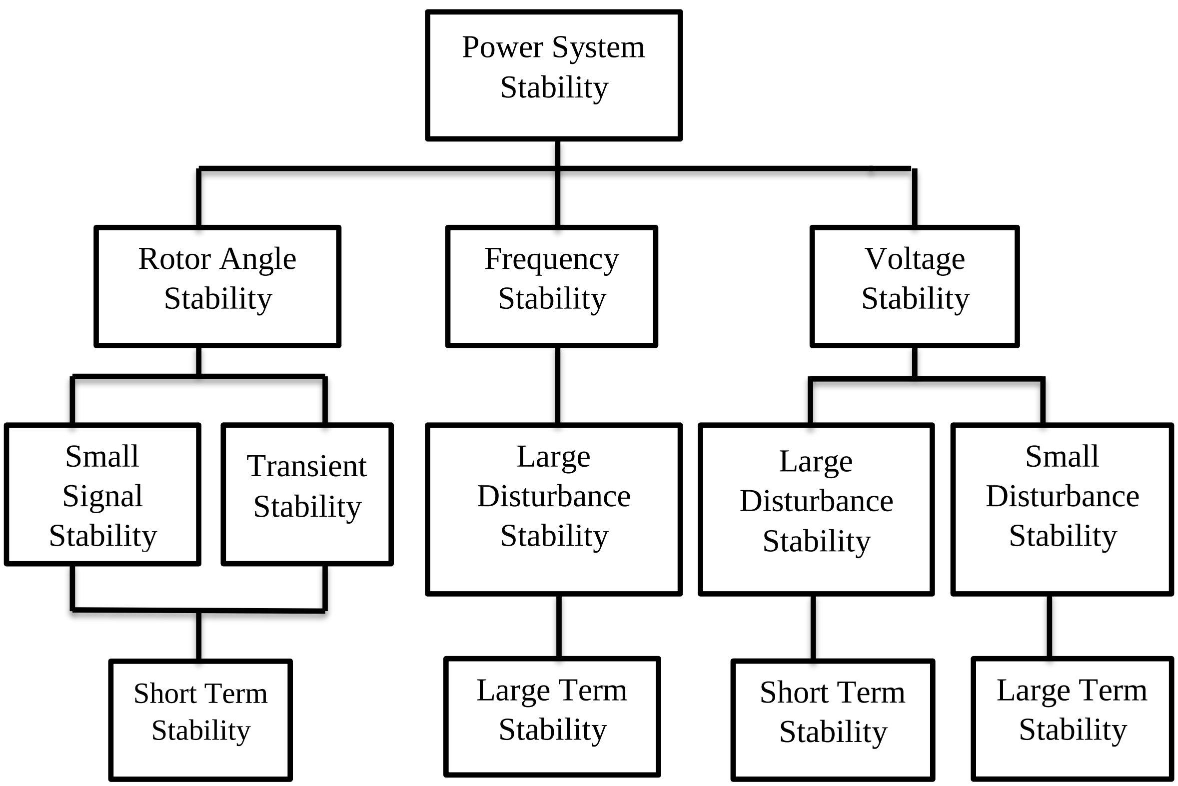

Figure 2.1 Classification of power system stability

Stability is conducted at planning level when new generating and transmitting facilities are developed. The studies are needed in determining the relaying system needed, critical fault clearing time of circuit breaker, critical clearing angle, auto reclosing time t_{cr} , voltage level and transfer capability between system. When the power system loss stability, the machines

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will lose synchronization and it will no longer working at synchronous speed. This will lead to power, voltage and current to oscillate drastically. It can cause damage to the loads which receive electric supply from the instable system. The stability of a system refers to the ability of a system to return back to its steady state when subjected to a disturbance. Power is generated by synchronous generators that operate in synchronism with the rest of the system. A generator is synchronized with a bus when both of them have same frequency, voltage and phase sequence.

Power system stability can be defined as the ability of the power system to return to steady state without losing synchronism. Usually power system stability is categorized into Steady State, Transient and Dynamic Stability. Compare to the steady state, the transient stability must be given more attention since its influence greatly on the power system. Transient studies are needed to ensure that the system can withstand the transient condition following a major disturbance. Short circuit is a severe type of disturbance. During a fault, electrical powers from the nearby generators are reduced drastically, while powers from remote generators are scarily affected. In some cases, the system may be stable even with sustained fault; whereas in other cases system will be stable only if the fault is cleared with sufficient rapidity. Whether the system is stable on the occurrence of a fault depends not only on the system itself, but also on the type of fault, location of fault, clearing time and the method of clearing. Transient stability limit is almost always lower than the steady state limit and hence it is much important. Transient stability limit depends on the type of disturbance, location and magnitude of disturbance.

2.1.1 Stability Limits

There are two types of stability limit for a power system, namely steady-state stability limit and transient stability limit.

- **Steady-State Stability Limit**

The steady-state stability is defined as the stability of a system under conditions of gradual or small changes in the system. This stability can be either found by the Transient Stability calculation for a steady-state operation or determined by a transient stability study if there are system changes or disturbances involved. The system is said to be steady-state stable if,

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following any small and/or gradual disturbances, all synchronous machines reach their steady-state operating condition identical or close to the pre-disturbance operating conditions. The steady-state stability limit for any synchronous machine is when its power angle is less than 90 degrees.

- **Transient Stability Limit**

Transient or dynamic stability is defined as the stability of a system during and after sudden changes or disturbances in the system, such as short-circuits, loss of generators, sudden changes in load, line tripping, or any other similar impact. The system is said to be transient stable if following a severe disturbance, all synchronous machines reach their steady-state operating condition without prolonged loss of synchronism or going out of step with other machines. The transient stability limit for any synchronous machine is its power angle is less than 180 degrees.

2.2 Rotor Angle Stability

Rotor Angle Stability is the ability of interconnected synchronous of the power system to remain in synchronism. The stability problem involves the stability of the electromechanical oscillations inherent in the power systems. A fundamental factor in this problem is the manner in which the power output of synchronous machines varies as their rotors oscillate.

Rotor angle stability is mainly classified into two categories:

I. Small Signal (or Small Disturbances) Stability

II. Transient (or Large Disturbances) Stability

2.2.1 Small Signal (or Small Disturbances) Stability

Small Signal Stability is the ability of the power system to maintain synchronism under small disturbances. Such disturbances occur continually on the system because of small variations in loads and generations. The disturbances are considered sufficiently small for linearization of the system equations to be permissible for purpose analysis. Instability may result can be of two forms:

(i) steady increase in rotor angle due to lack of sufficient synchronizing torque

(ii) rotor oscillations of increasing amplitude due lack of sufficient damping torque.

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The nature of system response to small disturbances depends on several factors including the initial operating, the transmission system strength, and the type of generator excitation controls used. In today's practical power systems, small signal stability is largely a problem of insufficient damping of oscillations.

2.2.2 Transient (or Large Disturbances) Stability

Transient stability is the ability of the power system to maintain synchronism when subjected to a severe transient disturbance such as the occurrence of a fault, the sudden outage of a line or the sudden application or removal of loads. The resulting system response involves large excursions of generator rotor angles and is influenced by the nonlinear power-angle relationship. Following such sudden disturbances in the power system, rotor angular differences, rotor speeds, and power transfer undergo fast changes whose magnitudes are dependent upon the severity of disturbances. For a large disturbance, changes in angular differences may be so large as to cause the machine to fall out of step. This type of instability is known as transient instability. Transient stability is a fast phenomenon, usually occurring within one second for a generator close to the cause of disturbance. The objective of the transient stability study is to ascertain whether the load angle returns to a steady value following the clearance of the disturbance. Transient stability studies are related to the effect of the transmission line faults on generator synchronism. The transient instability phenomenon is a very fast one and occurs within one second or a fraction of it for generator close to location of disturbance.

During the fault, the electrical power from nearby generators is reduced and the power from remote generators remains relatively unchanged. The resultant differences in acceleration produce speed differences over the time interval of the fault and it is important to clear the fault as quick as possible. The fault clearing removes one or more transmission elements and weakens the system. The changes in the transmission system produce change in the generator rotor angles. If the changes are such that the accelerated machines pick up additional load, they slow down and a new equilibrium position is reached. The loss of synchronism will be evident within one second of the initial disturbance.

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Faults on heavily loaded lines are more likely to cause instability than the fault on lightly loaded lines because they tend to produce more acceleration during the fault. Three phase faults produce greater accelerations than those involving one or two phase conductors. Faults which are not cleared by primary fault produce more angle deviations in the nearby generators. Also, the backup fault clearing is performed after a time delay and hence produces severe oscillations. The loss of a major load or a major generating station produces significant disturbance in the system.

Figure 2.2 illustrates the behaviour of a synchronous machine for stable and unstable situations. It shows the rotor angle responses for a stable case and for two unstable cases. In the stable cases (Case 1), the rotor angle increases to a maximum, then decreases and oscillates with decreasing amplitude until it reaches a steady state. In case 2, the rotor angle continues to increase steadily until synchronism is lost. This form of instability is referred to as first-swing instability and is caused by insufficient synchronizing torque. In Case 3, the system is stable in the first swing but becomes unstable as a result of growing oscillations as the end state is approached. This form of instability generally occurs when the post-fault steady-state condition itself is "small-signal" unstable, and not necessarily as a result of the transient disturbance.

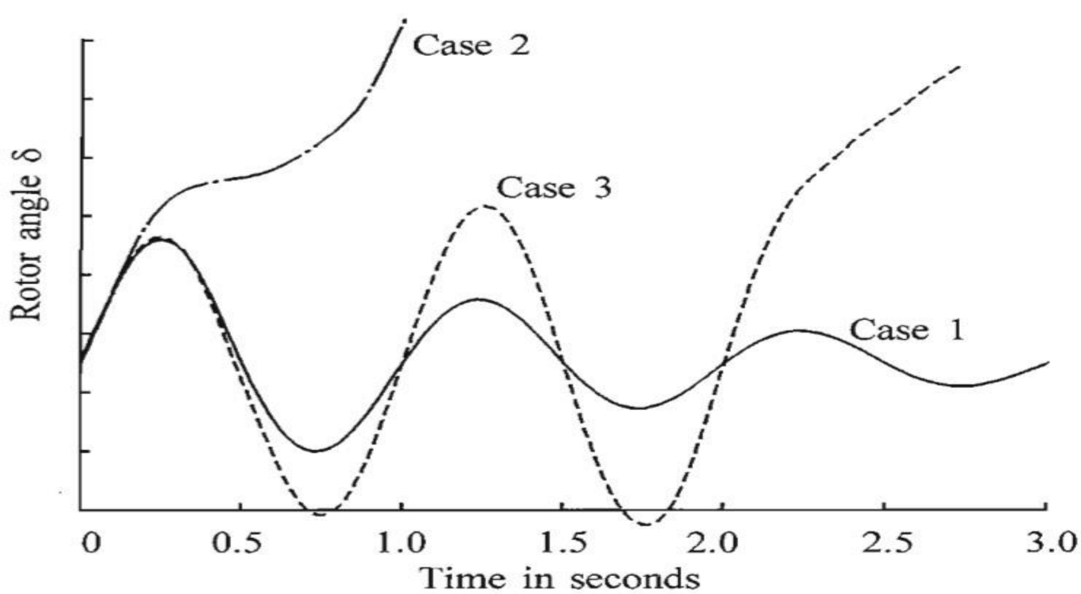

Figure 2.2 Rotor angle responses to a transient disturbance

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In large power systems, transient instability may not always occur as first-swing instability; it could be the result of the superposition of several modes of oscillation causing large excursions of rotor angle beyond the first swing. In transient stability studies the study period of interest is usually limited to 3 to 5 seconds following the disturbance, although it may extend to about ten seconds for very large systems with dominant inter area modes of oscillation.

Illustration of Transient Stability Phenomenon

Let us examine the response of the system to a three phase fault at location F on transmission circuit 2, as shown in fig a. the corresponding equivalent circuit, assuming a classical generator model, is shown in fig b. the fault is cleared by opening the circuit breakers at both ends of the faulted circuit, the fault clearing time depending on the relaying tome and breaker time.

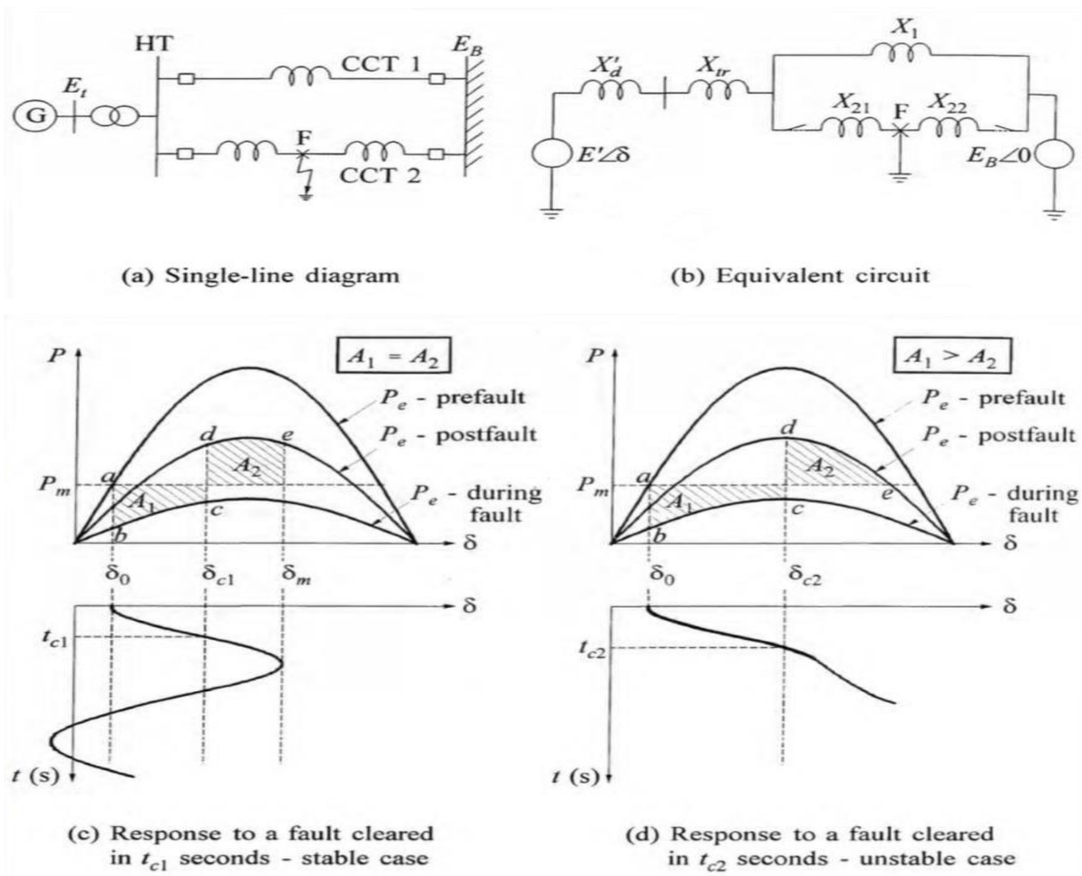

Figure 2.3 Illustration of transient stability phenomenon

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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 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 as shown in fig (a) and (b), some active power is transmitted to the infinite bus while the fault is still on.

Fig (c) and (d) show P_e- δ plot for the three network condition (1) pre-fault (2) with three phase fault on circuit 2 at a location some distance from the sending end, and (3) post fault. Fig (c) considers the system performance with a fault clearing time of t_{c1} and represents a stable case. Fig (d) considers a longer fault clearing time t_{c2} such that the system is unstable. In both cases P_m is assumed to be constant.

Let us examine the stable case depicted by fig(c). Initially, the system is operating with both circuit in service such that $P_e=P_m$ and $\delta= \delta_o$. When the fault occurs, the operating point suddenly changes from a to b. owing to inertia, angle δ cannot change instantly. Since P_m is now greater than P_e, the rotor accelerates until the operating point reaches c, when the fault is cleared by isolating circuit 2 from the system. The operating point now suddenly shifts to d. Now P_e is greater than P_m, causing deceleration of the rotor. Since the rotor speed is greater than the synchronous speed ω_0, δ continues to increase until the kinetic energy gained during the period of acceleration is expected by transferring the energy to the system. The operating point moves from d to e, such that area A_2 is equal to A_1. At point e, the speed is equal to ω_0 and δ has reached its maximum value δ_m. since P_e is still greater than P_m, the rotor continues to retard, with the speed dropping below ω_0, the rotor angle δ decreases, and the operating point retraces the path from e to d and follows the P_e - δ curve for the post fault system farther down. The minimum value of δ is such that it satisfies the equal-area criterion for the post fault system. In the absence of any source of damping, the rotor continues to oscillate with constant amplitude.

With a delayed fault clearing as shown in fig (d) area A_2 above P_m is less than A_1. When the operating point reaches e, the kinetic energy gained during the accelerating period has not yet

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been completely expended, consequently the speed is still greater than ω_o and δ continues to increase. Beyond point e, P_e is less than P_m, and the rotor begins to accelerate again. The rotor speed and angle continue to increase, leading to loss in synchronism.

Synchronous Machine Power Angles

Synchronous machines play a decisive role in the power system stability because during and after disturbances their power angles (also referred as rotor angles) will oscillate to cause power flow oscillations in the system. Depending on the level of these oscillations, the electromechanical equilibrium in the system could be destroyed and the instability could occur. Therefore, power system stability is sometimes also referred to as synchronous machine power angle stability.

The following two equations are often referenced in power system transient stability studies:

Torque Equation (Generator Case)

$$T = \frac{\pi P^2}{8} \phi_{air} F_r \sin\delta \quad \text{..} \mathbf{(2.1)}$$

where,

T	=	mechanical shaft torque
P	=	number of poles
φ_{air}	=	air-gap flux
F_r	=	rotor field MMF
Δ	=	power (rotor) angle

The torque equation defines the relationship between the mechanical shaft torque, the stator voltage, the excitation system, and the power angle. Changes in any one of them will cause the power angle to readjust itself to a new position.

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Swing Equation (Generator Case)

$$M\frac{d^2\delta}{dt^2} + D\frac{d\delta}{dt} = P_{mech} - P_{elec} \quad \text{...(2.2)}$$

where,

M = inertia constant

D = damping constant

P_{mech} = input mechanical power

P_{elec} = output electrical power.

The swing equation shows that the solution of the power angle is a function of balance between the mechanical power and the electrical power. Any change in the system that breaks this balance will cause the power angle to undergo a transient and reach a new position in an oscillatory manner. This oscillation is usually called the power angle swing.

2.2.3 Equal Area Criterion

The accelerating power in swing equation will have sine term. Therefore, the swing equation is non-linear differential equation and obtaining its solution is not simple. For two machine system and one machine connected to infinite bus bar, it is possible to say whether a system has transient stability or not, without solving the swing equation. Such criteria which decides the stability, makes use of equal area in power angle diagram and hence it is known as Equal Area Criterion (EAC). Thus the principle by which stability under transient conditions is determined without solving the swing equation, but makes use of areas in power angle diagram, is called Equal Area Criterion.

EAC is an old graphical method that allows assessing the transient stability of electric power systems in a simple and comprehensive way. This method was developed and popularized at the end of the 30's and its origin is not very well known. It is mainly used for the assessment of transient stability of one-machine connected to an "infinite" bus (or of a two-machine system). One of the main appealing characteristics of EAC is that its use eliminates the need of computing the swing curves of the system, thus saving a considerable amount of work,

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even if, in its “pure” statement, very simplified assumptions were made regarding power system modelling.

Indeed, the system is represented by the classical model having the following features:

- synchronous machines are represented by a constant voltage source behind the transient reactance
- synchronous machines have constant mechanical power and negligible damping loads are represented by constant impedance characteristics.

2.3 Performance of Protective Relaying

Protective relay detects the existence of abnormal system conditions by monitoring appropriate system quantities, determine which circuit breakers should be opened, and energized trip circuit of those breakers.

To perform their functions satisfactorily, relays should satisfy three basic requirements:

- Selectivity
- Speed
- Reliability

Since transient stability is concerned with the ability of the power system to maintain synchronism when subjected to a several disturbances, satisfactory performance of certain protection system is of paramount importance in ensuring system stability. While the relays should initiate circuit breaker operations to clear faulted element, it is important to ensure that there are no further relaying operation that cause unnecessary opening of unfaulted elements, during stable power swing. Tripping of unfaulted elements would weaken the system further and could lead to system un-stability. One of the important aspects the transient stability analysis, then is the evaluation of the performance of protective system during the transient period, particularly the performance of relaying used for protection of transmission line and generators.

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2.3.1 Transmission Line Protection

There are a variety of line protection schemes and practice used by utilities to meet particular system requirement. The following factors influence the choice of the protection scheme:

- Types of circuit breakers: single line, parallel line, multi terminal, magnitude of fault current in fed etc.
- Function of lines its effect on service continuity speed with which fault has to be cleared.
- Co-ordination and matching requirements.

The basic types of relaying schemes are used for line protection:

- Overcurrent relaying
- Distance relaying
- Pilot relaying

Overcurrent relaying is used in principally on sub-transmission system and radial disturbance system since fault on these systems usually do not affect system stability, high speed protection is not required (overcurrent relaying cannot discriminate between load and fault). A distance relay responses to a ratio of measured voltage to measure current. A relay operates if the ratio, which represents the effective impedance of the network is less than the relay setting. Impedance is measure of distance along the transmission line and therefore the relay is known as distance relay. The impedance approach provides an excellent way of obtaining discrimination and selectivity, by limiting relay operation to a certain range of the impedance. Pilot relaying scheme utilizes communication channels between the terminals of the line that may protect.

2.3.2 Fault Clearing Time

The removal of a faulted element requires a protective relay system to detect that a fault has occurred and to initiate the opening of circuit breaker which will isolate the faulted element from the system. The total fault clearing time is, therefore, made up of the relay time and breaker interrupting time. The relay time is the time from the initiation of the short circuit current to the initiation of the trip signal to the circuit breaker. The interrupting time is the

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time from the initiation of the trip signal to the interruption of the current through the breaker. On high voltage (HV) and extra high voltage (EHV) transmission systems, the normal relay times range from 15 to 30 ms (1 to 2 cycles) and circuit breaker interrupting times range from 30 to 70 ms (2 to 4 cycles).

2.3.3 Prevention of Tripping during Transient Conditions

Requirements for prevention of tripping during swing conditions generally fall into two categories:

- Prevention of tripping during stable swings while allowing tripping for unstable transients.
- Prevention of tripping during unstable transients and forcing of separation at another point.

2.3.4 Automatic Line Reclosing

The majority (60 to 80 %) of transmission line faults are of a transitory nature. An example of such a fault is an insulator flashover due to high transient voltages induced by lightning. After the line is de-energized long enough for the fault source to pass and the fault arc to de-ionized, the line may be reconnected. Therefore, common practice is reclosing the circuit breaker automatically to improve service continuity. The reclosing may be either single-shot (one attempt) or multi-shot (several attempts) with time delay between each attempt. If the fault persists after two or three attempts, the operator may attempt to reclose manually after some delay.

2.3.5 Generator Out-of-Step Protection

For situation where the electrical centre is out in the transmission system, the detection of an out-of-step condition and the isolation of unstable generators are finished by line protection. However, for situations where the electrical centre is within the generator or step-up transformer, a special relay must be provided at the generator. Such a situation occurs when a generator pulls out of synchronism in a system with strong transmission. A low excitation level on the generator also tends to contribute to such a condition.

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3 SINGLE MACHINE CONNECTED TO INFINITE BUS

The bus whose voltage and frequency remains constant even after the variation in the load is known as the infinite bus. The alternators operating in parallel in a power system is the example of the infinite bus. The on and off of any of the alternator will not affect the working of the power system.

The capacity of a parallel operating system is enormous. Their voltage and frequency remain constant even after the disturbance of the load. The connection and disconnection of any of the machine will not affect the magnitude and phase of voltage and frequency of an infinite bus. In an infinite bus system,

- The voltage and frequency always remain constant.
- The synchronous impedance of the bus is low because of parallel operations of the machine.

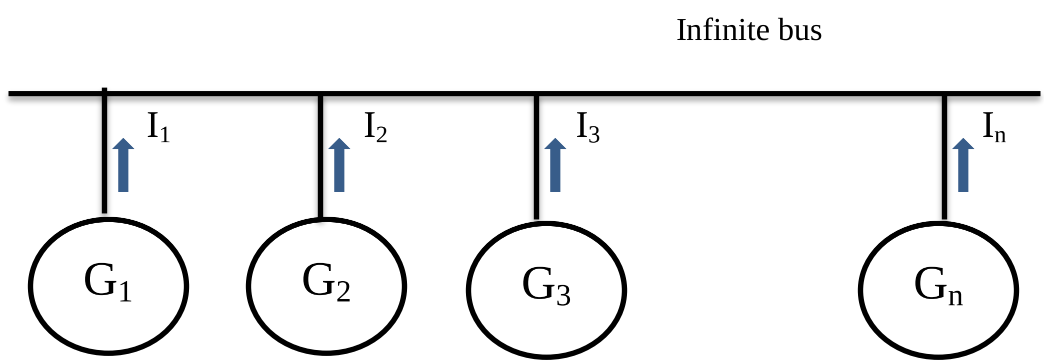

Figure 3.1 Infinite bus

The performance of the synchronous machine varies on the infinite bus. When the synchronous machine operates independently, variation in their excitation causes the changes in their terminal voltage. The power factor of the synchronous machine depends only on their load. But when the synchronous machines are operating in parallel, the change in their excitation changes the power factor of the load.

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3.1 Illustration I (Simulation in MATLAB)

A three-phase generator rated 200 MVA, 13.8 kV, 112.5 rpm is connected to a 230 kV, 10,000 MVA network through a Delta-Wye 210 MVA transformer. At t = 0.1 s, a three-phase to ground fault occurs on the 230 kV bus. The fault is cleared after 6 cycles (t = 0.2 s).

The machine reactive power, mechanical power and field voltage requested to supply the electrical power is: Q = 3.4 MVar; P_{mec} = 150.32 MW (0.7516 pu); field voltage E_f = 1.291 pu.

The terminal voltage Va is 1.0 p.u. at the beginning of the simulation. It falls to about 0.4 pu during the fault and returns to nominal quickly after the fault is cleared. This quick response in terminal voltage is due to the fact that the Excitation System output Vf can go as high as 11.5 pu which it does during the fault. The speed of the machine increases to 1.01 pu during the fault then it oscillates around 1 p.u. as the governor system regulates it. The speed takes much longer than the terminal voltage to stabilize mainly because the rate of valve opening/closing in the governor system is limited to 0.1 pu/s.

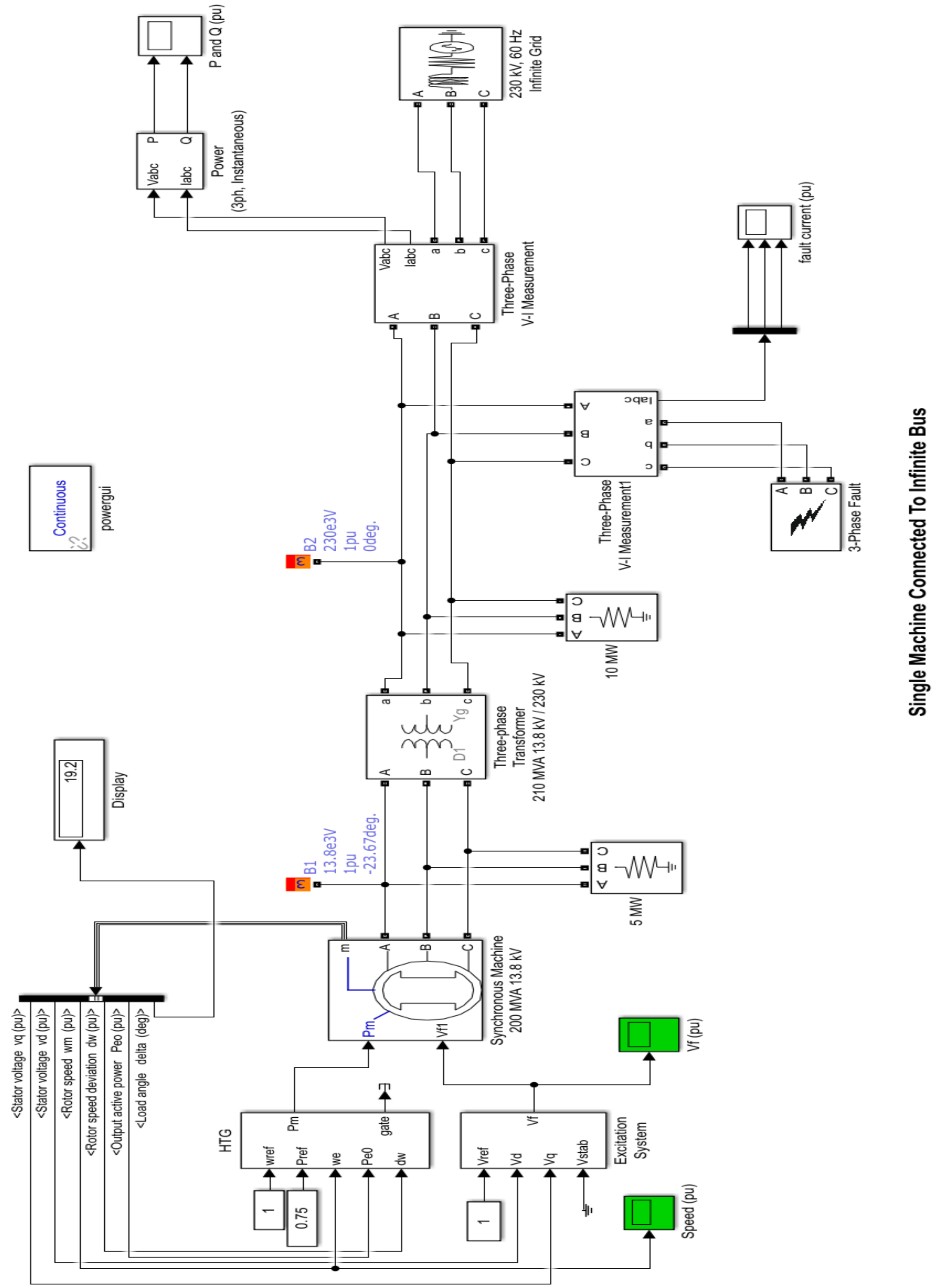

Figure 3.2 Single machine connected to infinite bus

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Outputs

The outputs obtained after running the simulation are presented below.

Case I: Stable System

Scope 1

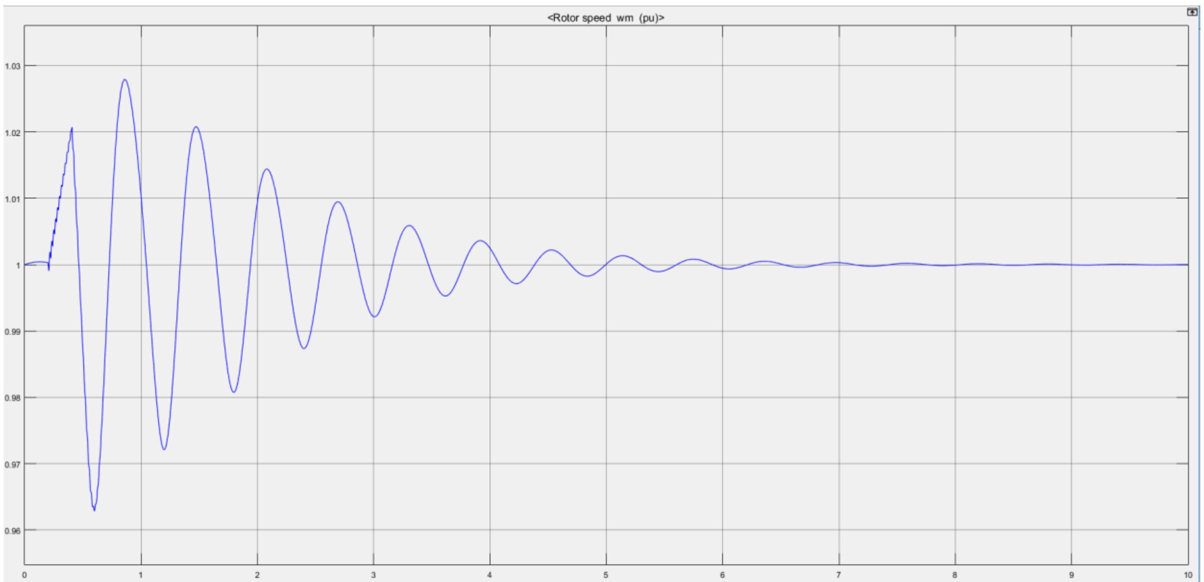

Figure 3.3 Rotor speed in pu

Scope 2

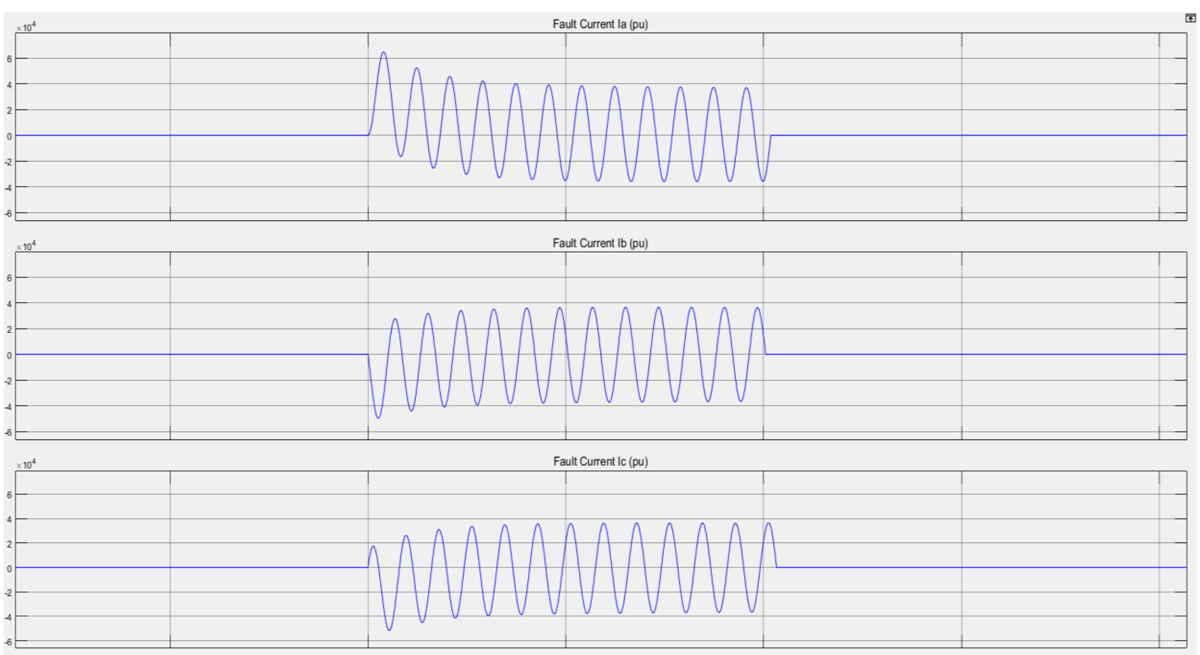

Figure 3.4 Fault current

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Scope 3

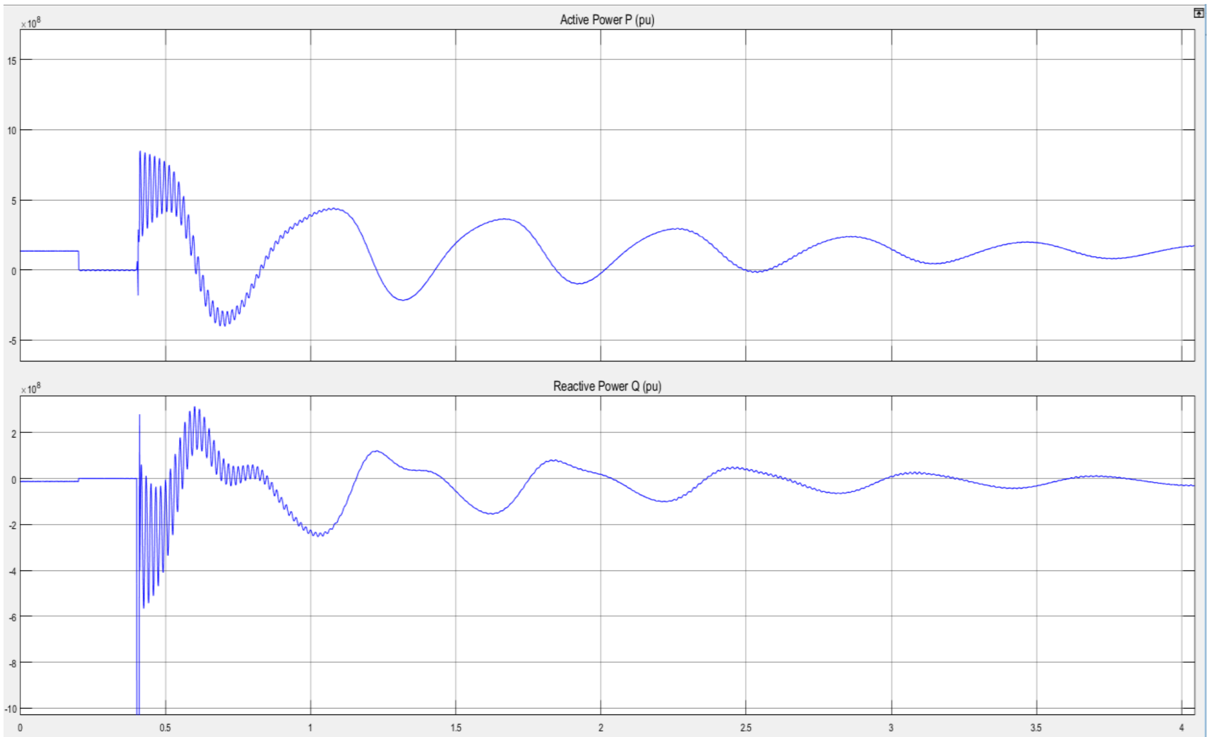

Figure 3.5 Active and reactive powers

Case II: Unstable System

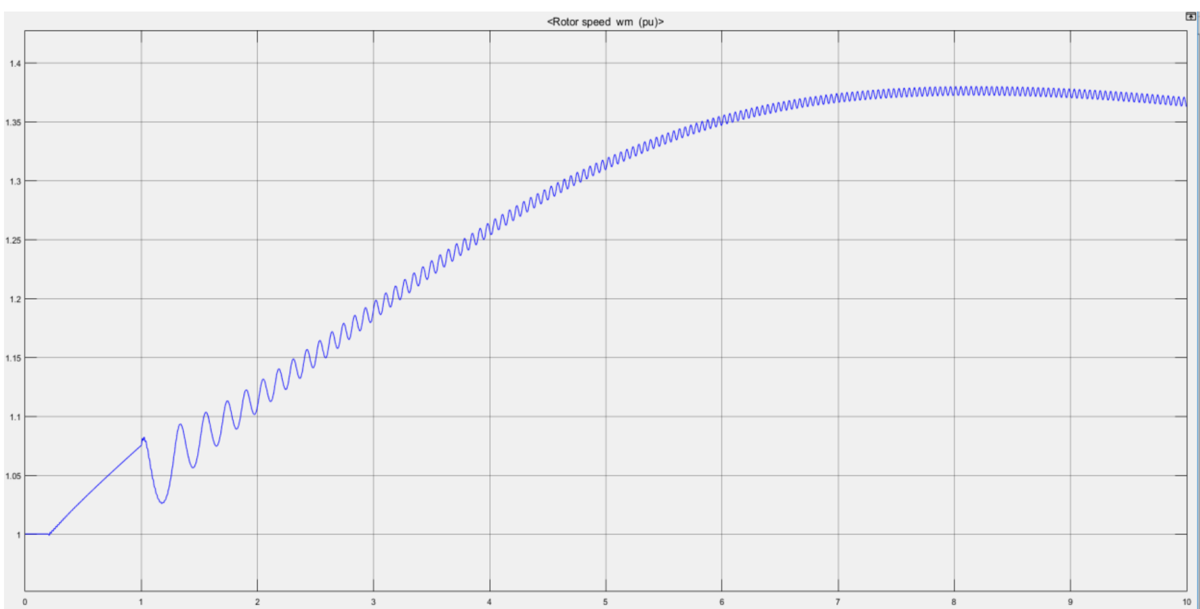

Figure 3.6 Rotor speed in pu

`

3.2 Illustration II (Motion of the Rotor Angle and the Generator Frequency)

A 60-Hz synchronous generator having inertia constant H = 9.94 MJ/MVA and a transient reactance X'_d = 0.3 per unit is connected to an infinite bus through a purely reactive circuit as shown in Figure 3.7. Reactances are marked on the diagram on a common system base. The generator is delivering real power of 0.6 per unit, 0.8 power factor lagging to the infinite bus at a voltage of V = 1 per unit.

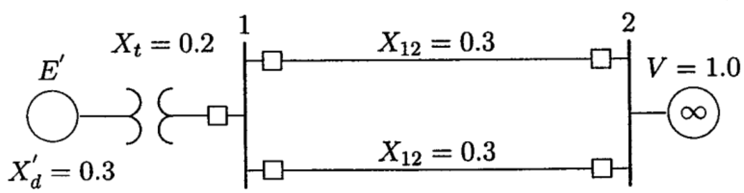

Figure 3.7 Single line diagram of Illustration II

Assume per unit damping power coefficient is D = 0.138. Consider a small disturbance of $\Delta\delta = 10^0 = 0.1745\, radian$. For example, the breakers open and then quickly close. Obtain equations describing the motion of the rotor angle and the generator frequency.

Solution:

The transfer reactance between the generated voltage and the infinite bus is

X = 0.3 +0.2 + 0.3 = 0.65 pu

The per unit apparent power is

$$S = \frac{0.6}{0.8} \measuredangle \cos^{-1} 0.8 = 0.75\measuredangle 36.87°$$

The current is

$$I = \frac{S^*}{V^*} = \frac{0.75\measuredangle -36.87°}{1.0\measuredangle 0°} = 0.75\measuredangle - 36.87°$$

The excitation voltage is

$$\mathrm{E}' = \mathrm{V} + \mathrm{jXI} = 1.0\measuredangle 0° + (\mathrm{j}0.65)(0.75\measuredangle - 36.87°) = 1.35\measuredangle 16.79°$$

`

Thus, the initial operating power angle is 16.79° = 0.2931 radian. The synchronizing power coefficient given by (11.39) is

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

$= \frac{1.35*1}{0.65}\cos 16.79\,°$

=1.9884

The undamped angular frequency of oscillation and damping ratio are

$$\omega_n = \sqrt{P_S * \frac{\pi f_0}{H}}$$

$$= \sqrt{\frac{60 * \pi}{9.94} * 1.9884} = 6.1405\, rad/sec$$

$$\zeta = \frac{D}{2}\sqrt{\frac{\pi f_0}{HP_s}} = \frac{0.138}{2}\sqrt{\frac{60\pi}{9.94{*}1.9884}} = 0.2131$$

The linearized force-free equation which determines the mode of oscillation is

$$\frac{d^2\Delta\delta}{dt^2} + 2.62\frac{d\Delta\delta}{dt} + 37.7\Delta\delta = 0$$

From (11.50), the damped angular frequency of oscillation is

$$\omega_d = \omega_n\sqrt{1-\zeta^2} = 6.1405\sqrt{1-0.2131^2} = 0.213$$

corresponding to a damped oscillation frequency of

$$f_d = \frac{6.0}{2\pi} = \text{ 0.9549 Hz}$$

The motion of rotor relative to the synchronously revolving field in electrical degrees and the frequency excursion in Hz are given by equations

$\delta = 16.79° + 10.234e^{-1.3t}\sin(6.0t + 77.6966°)$

$f = 60 - 0.1746e^{-1.3t}\sin 6.0t$

`

The above equations are written in MATLAB commands as follows:

Output

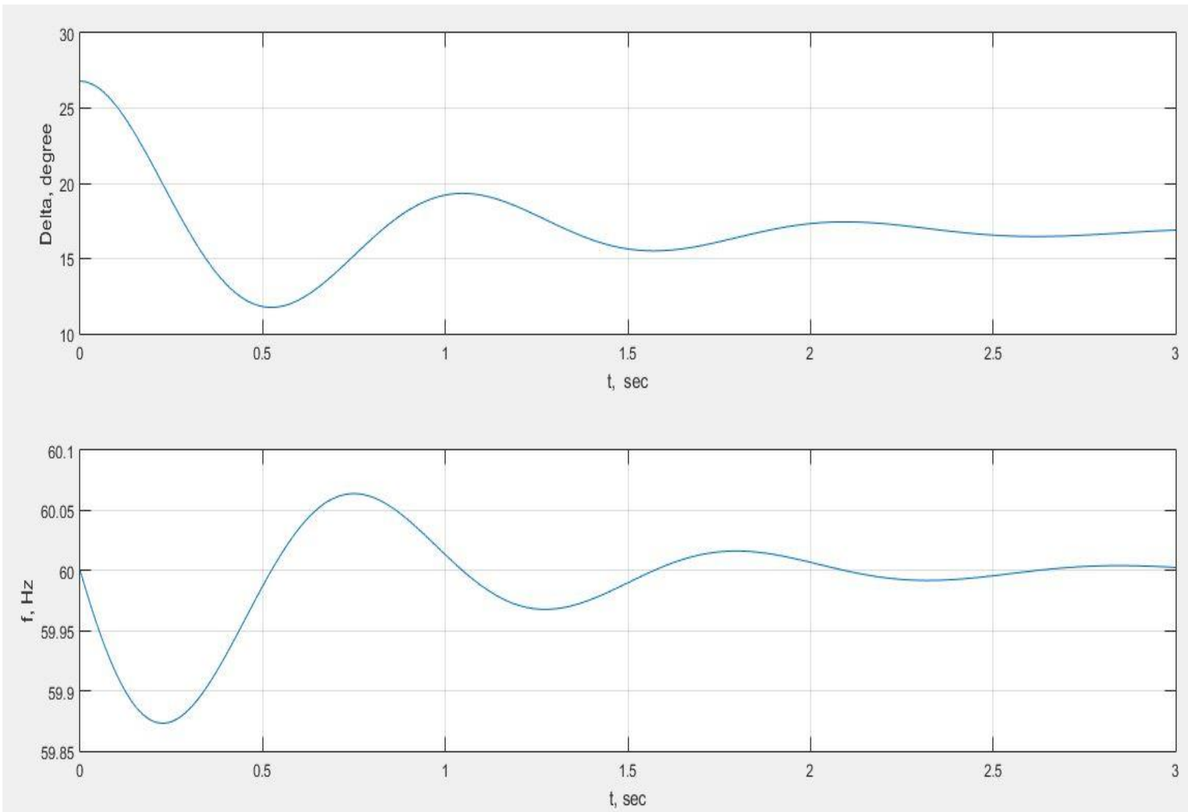

Figure 3.8 Natural response of rotor angle and frequency for machine of Illustration II

The result is shown in Figure 3.8.

The response shows that a small disturbance will be followed by a relatively slowly damped oscillation, or swing, of the rotor, before steady state operation at synchronous speed is resumed. In the case of a steam turbine generator, oscillations subside in a matter of two to three seconds. In the above example, the response settles in about $t_s \approx 4 = 4(1/1.3) \approx 3.1$ seconds. We also observe that the oscillations are fairly low in frequency, in the order of 0.955 Hz.

`

3.3 Illustration III

The generator of Illustration II is operating in the steady state at δ_0= 16.799^0 when the input power is increased by a small amount ΔP = 0.2 per unit. The generator excitation and the infinite bus bar voltage are the same as before, i.e., E' = 1.35 per unit and V = 1.0 per unit. Obtain the step response for the rotor angle and the generator frequency.

Solution:

The motion of rotor relative to the synchronously revolving field in electrical radian is

$$\delta = \delta_0 + \frac{\pi f_0 \Delta \mathrm{P}}{H{\omega_n}^2}[1 - \frac{1}{\sqrt{1-\zeta^2}} e^{-\zeta\omega_n t}\sin(\omega_d t + \theta)]$$

and the rotor angular frequency in radian per second is

$$\omega = \omega_0 + \frac{\pi f_0 \Delta \mathrm{P}}{H\omega_n\sqrt{1-\zeta^2}} e^{-\zeta\omega_n t}\sin\omega_d t$$

Substituting for H, δ_0 , ζ , and ω_n evaluated in Illustration II and expressing the power angle in degree, we get

$$\delta = 16.79° + \frac{180 * 60 * 0.2}{9.94 * (6.1405)^2}[1 - \frac{1}{\sqrt{1-(0.2131)^2}} e^{-1.3t}\sin(6t + 77.6966°)]$$

$$\delta = 16.79° + 5.7631[1 - 1.0235 e^{-1.3t}\sin(6t + 77.6966°)]$$

Also, substituting the values in (11.76) and expressing the frequency in Hz, we get

$$f = 60 + \frac{60*0.2}{2*9.94*6.1405\sqrt{1-(0.2131)^2}} e^{-1.3t}\sin 6t$$

or, f = 60+ $0.10 e^{-1.3t}\sin 6t$

The above functions are plotted over a range of 0 to 3 seconds and the result is shown in figure 3.9.

Codes: Refer Appendix

`

Output

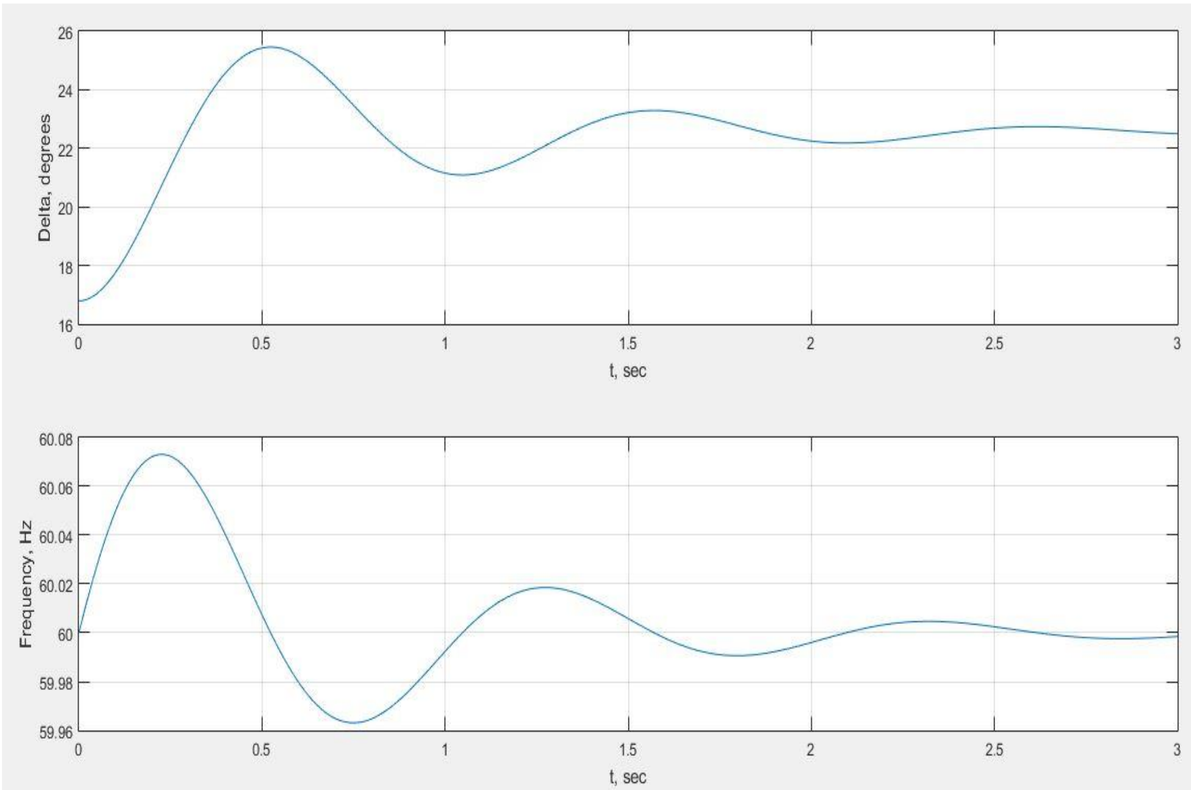

Figure 3.9 Step response of rotor angle and frequency for machine of Illustration III

3.4 Illustration IV

The machine of Illustration II is delivering a real power of 0.6 per unit, at 0.8 power factor lagging to the infinite bus bar. The infinite bus bar voltage is 1.0 per unit. Determine the maximum power input that can be applied without loss of synchronism.

Solution:

In Illustration II, the transfer reactance and the generator internal voltage were found to be X = 0.65 pu, and E' = 1.35 pu .

Codes : Refer Appendix

`

Commands

P0 = 0.6; E = 1.35; V = 1.0; X = 0.65;

eacpower (P0, E, V, X)

Results

Initial power	= 0.600 p.u.
Initial power angle	= 16.791 degrees
Sudden additional power	= 1.084 p.u.
Total power for critical stability	= 1.684 p.u.
Maximum angle swing	=125.840 degrees
New operating angle	= 54.160 degrees

Output

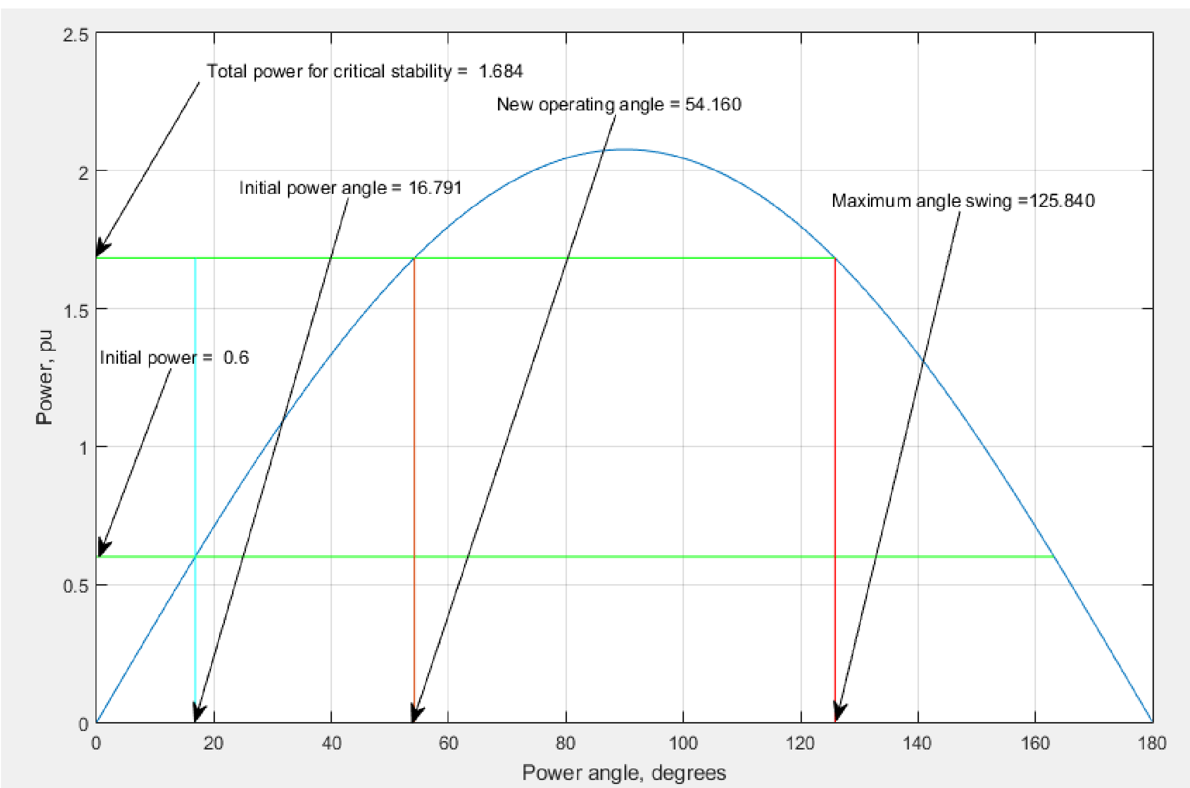

Figure 3.10 Maximum power limit by Equal Area Criterion for Illustration IV

`

3.5 Illustration V

A 60-Hz synchronous generator having inertia constant H = 5 MJ/MVA and a direct axis transient reactance X = 0.3 per unit is connected to an infinite bus through a purely reactive circuit as shown in Figure 3.11. Reactances are marked on the diagram on a common system base. The generator is delivering real power P_e = 0.8 per unit and Q = 0.074 per unit to the infinite bus at a voltage of V = 1 per unit.

(a) A temporary three-phase fault occurs at the sending end of the line at point F. When the fault is cleared, both lines are intact. Determine the critical clearing angle and the critical fault clearing time.

(b) A three-phase fault occurs at the middle of one of the lines, the fault is cleared, and the faulted line is isolated. Determine the critical clearing angle.

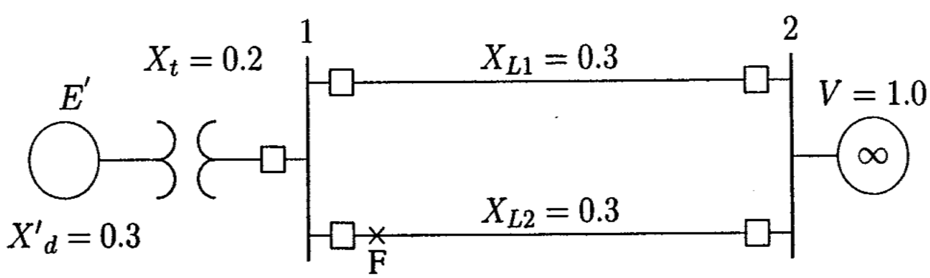

Figure 3.11 One-line diagram for Illustration V

Solution:

The current flowing into the infinite bus is

$$I = \frac{S^*}{V^*} = \frac{0.8 - j0.074}{1.0\measuredangle 0^0} = 0.8 - j0.074\, pu$$

The transfer reactance between internal voltage and the infinite bus before fault is

$X_1 = 0.3 + 0.2 + 0.3/2 = 0.65$

The transient internal voltage is

$E' = V + jX_1I = 1.0 + (j0.65)(0.8 - j0.074) = 1.17\measuredangle 26.387° \text{ pu}$

`

(a) Since both lines are intact when the fault is cleared, the power angle equation before and after the fault is

$$P_{max} sin\delta = \frac{1.17*1.0}{0.65} sin\delta = 1.8 sin\delta$$

The initial operating angle is given by

1.8 sin δ_0 = 0.8

or,

δ_0=26.388° = 0.46055 rad

And referring to Figure 3.15,

δ_{max}= 180° - δ_0 = 153.612° = 2.681 rad

Since the fault is at the beginning of the transmission line, the power transfer during fault is zero, and the critical clearing angle is

$\cos \delta_c = \frac{0.8}{1.8}$(2.681 -0.46055) + cos 153.61° = 0.09106

Thus, the critical clearing angle is

δ_c = $\cos^{-1}$(0.09106) = 84.775^0 = 1.48 rad

From the critical clearing time is given by

$$t_c = \sqrt{\frac{2H(\delta_c - \delta_0)}{\Pi f_0 P_m}}$$

$$= \sqrt{\frac{2 * 5 * (1.48 - 0.46055)}{\Pi * 60 * 0.8}}$$

= 0.26 second

The use of function eacfault(P_m, E, V, X_1, X_2, X_3) to solve the above problem and to display power-angle plot with the shaded equal-areas is demonstrated below. We use the following codes and commands:

`

Codes: Refer Appendix

Command

eacfault

Generator output power in p.u.	Pm = 0.8
Generator e.m.f. in p.u.	E = 1.17
Infinite bus-bar voltage in p.u.	V = 1.0
Reactance before Fault in p.u.	X1 = 0.65
Reactance during Fault in p.u.	X2 = inf
Reactance aftere Fault in p.u.	X3 = 0.65

For this case tc can be found from analytical formula.

To find tc enter Inertia Constant H, (or 0 to skip) H = 5

Output

Initial power angle	= 26.388
Maximum angle swing	= 153.612
Critical clearing angle	= 84.775
Critical clearing time	= 0.260 sec.

`

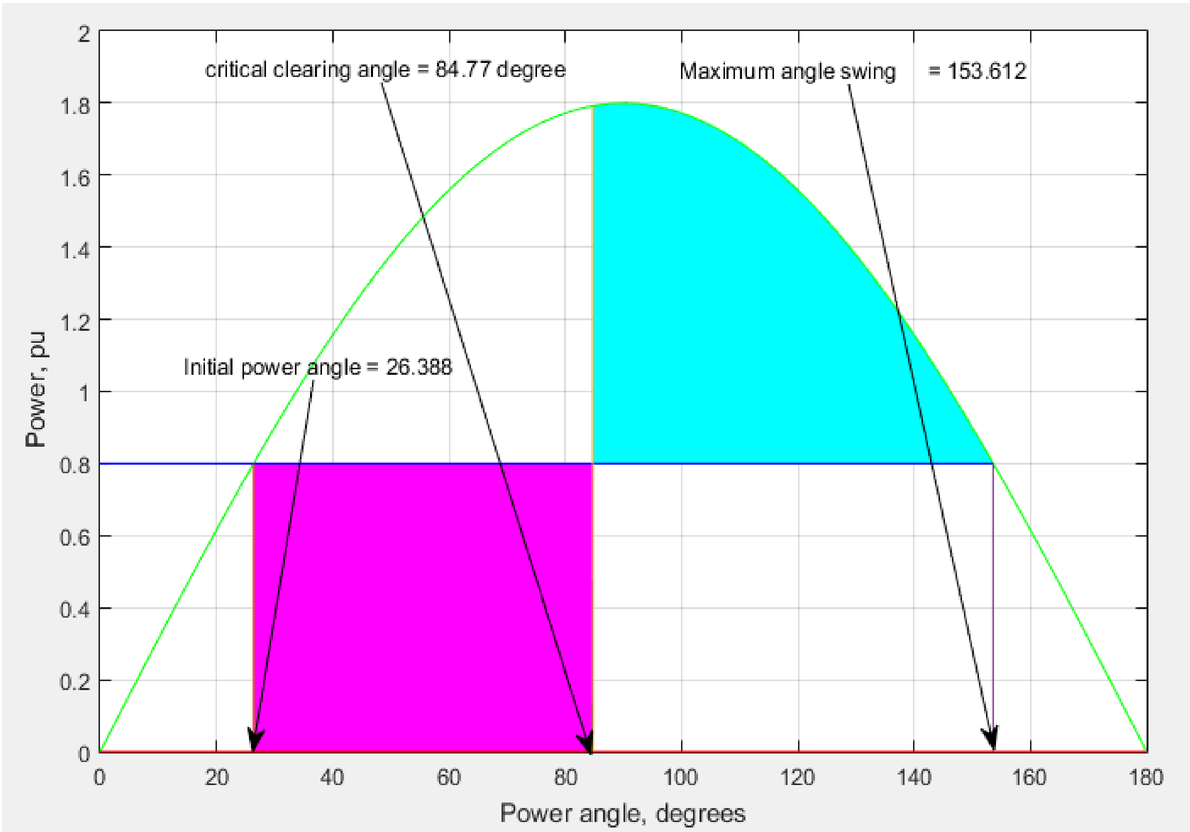

Figure 3.12 Power angle curve for Illustration V (a)

(b) The power angle curve before the occurrence of the fault is the same as before, given by

$P_{1max} = 1.8 \sin \delta$

The generator is operating at the initial power angle $\delta_o = 26.4° = 0.4605$ rad. The fault occurs at point F at the middle of one line, resulting in the circuit shown in Figure 3.13. The transfer reactance during fault may be found most readily by converting the Y-circuit ABF to an equivalent delta, eliminating junction C. The resulting circuit is shown in Figure 3.14.

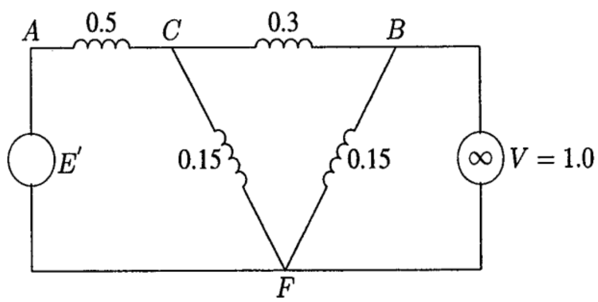

Figure 3.13 Equivalent circuit with three-phase fault at the middle of one line

`

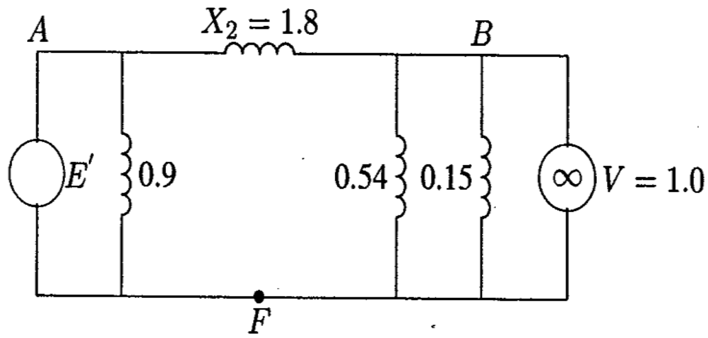

Figure 3.14 Equivalent circuit after Y- Δ transformation

The equivalent reactance between generator and the infinite bus is

$$X_2 = \frac{(0.5*0.3)+(0.5*0.15)+(0.3*0.15)}{0.15} = 1.8\,pu$$

Thus, the power-angle curve during fault is

$$P_{2max} sin\delta = \frac{1.17 * 1.0}{1.8} sin\delta = 0.65 sin\delta$$

When fault is cleared the faulted line is isolated. Therefore, the post fault transfer reactance is

X3 = 0.3+0.2+0.3=0.8 pu

and the power-angle curve is

$$P_{3max} sin\delta = \frac{1.17 * 1.0}{0.8} sin\delta = 1.4625 sin\delta$$

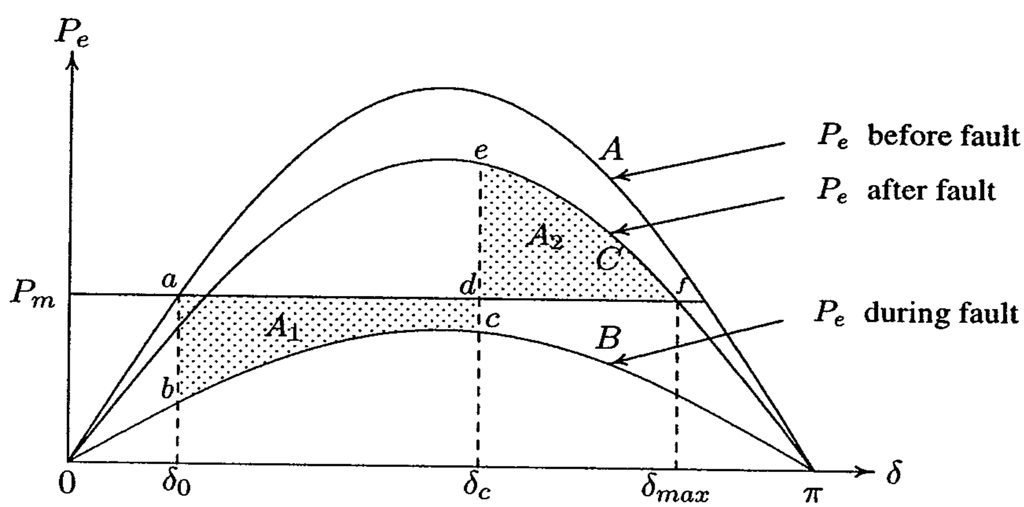

Figure 3.15 Equal Area Criterion for critical clearing angle

`

Referring to Figure 3.15,

δ_{max}= 180° - $\sin^{-1}(\frac{0.8}{1.4625})$ = 146.838° = 2.5628 rad

The critical clearing angle is given by

$$\cos\delta_c = \frac{P_{m(\delta_{max}-\delta_0)+P_{3max}cos\delta_{max}-P_{2max}cos\delta_0}}{P_{3max}-P_{2max}}$$

or, $\cos\delta_c = \frac{0.8(2.5628-0.46055) + 1.4625 \cos 146.838° - 0.65 \cos 26.388°}{1.4625 - 0.65}$

= -0.15356

Thus, the critical clearing angle is

$\delta_c = cos^{-1}(-0.15356) = 98.834°$

Function eacfault(Pm, E, V, X_1, X_2, X_3) is used to solve part (b) and to display power-angle plot. We use the following codes and commands:

Codes: Refer Appendix

Commands

eacfault

Generator output power in p.u. Pm = 0.8

Generator e.m.f. in p.u. E = 1.17

Infinite bus-bar voltage in p.u. V = 1.0

Reactance before Fault in p.u. X1 = 0.65

Reactance during Fault in p.u. X2 = 1.8

Reactance aftere Fault in p.u. X3 = 0.8

`

Output

Initial power angle = 26.388

Maximum angle swing = 146.838

Critical clearing angle = 98.834

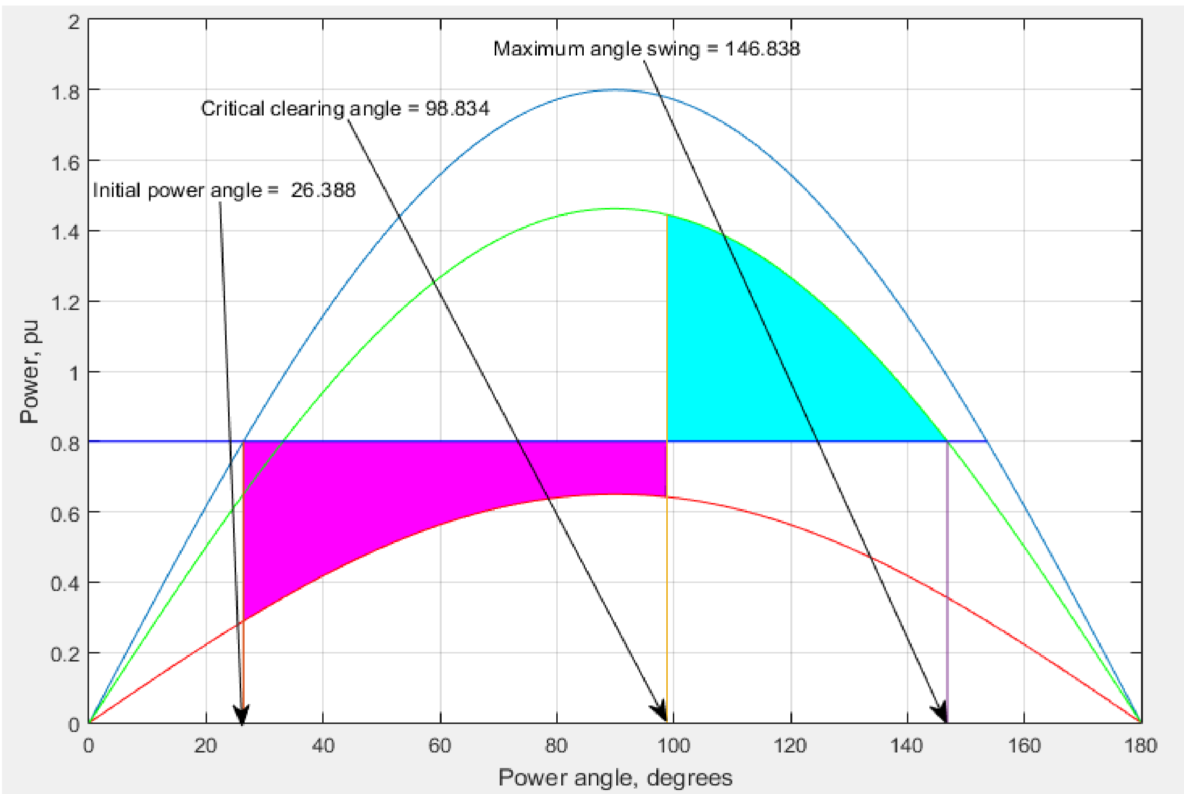

Figure 3.16 Equal Area Criterion for Illustration V (b)

`

4 MULTI-MACHINE SYSTEM

Multimachine equations can be written similar to the one-machine system connected to the infinite bus. In order to reduce the complexity of the transient stability analysis, similar simplifying assumptions are made as follows:

- Each synchronous machine is represented by a constant voltage source behind the direct axis transient reactance. This representation neglects the effect of saliency and assumes constant flux linkages.
- The governor's action is neglected and the input powers are assumed to remain constant during the entire period of simulation.
- Using the pre-fault bus voltages, all loads are converted to equivalent admittances to ground and are assumed to remain constant.
- Damping or asynchronous powers are ignored.
- The mechanical rotor angle of each machine coincides with the angle of the voltage behind the machine reactance.
- Machines belonging to the same station swing together and are said to be coherent. A group of coherent machines is represented by one equivalent machine.

4.1 Illustration I Multi-Machine Infinite Grid Connected System (Using Simulation)

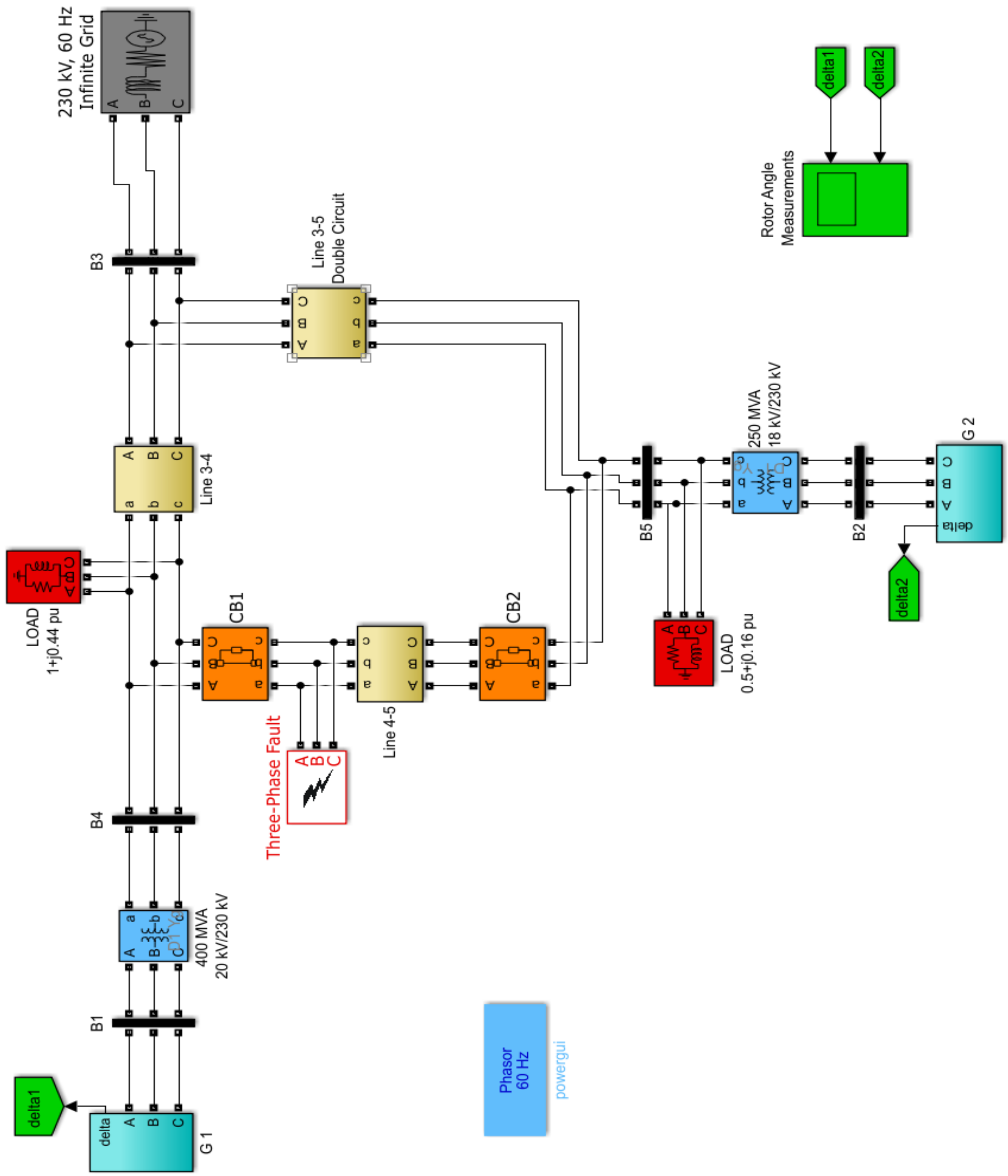

Figure 4.1 Multi-machine infinite grid connected system

Outputs:

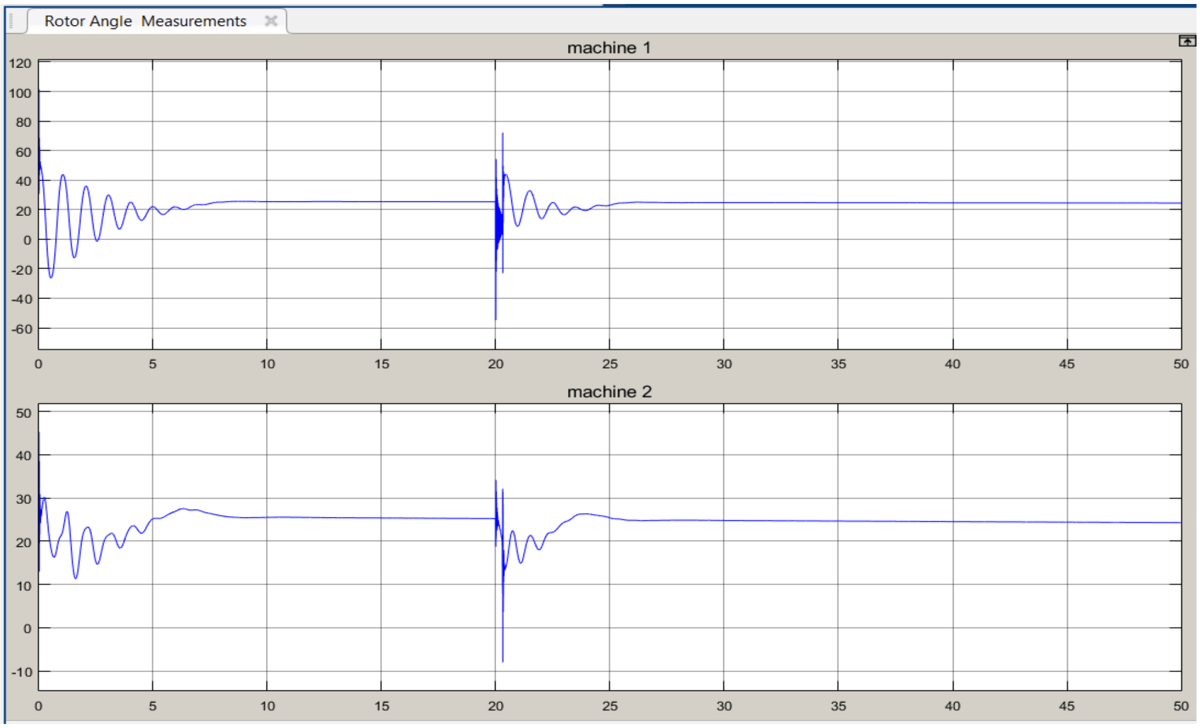

Figure 4.2 Rotor angle measurement

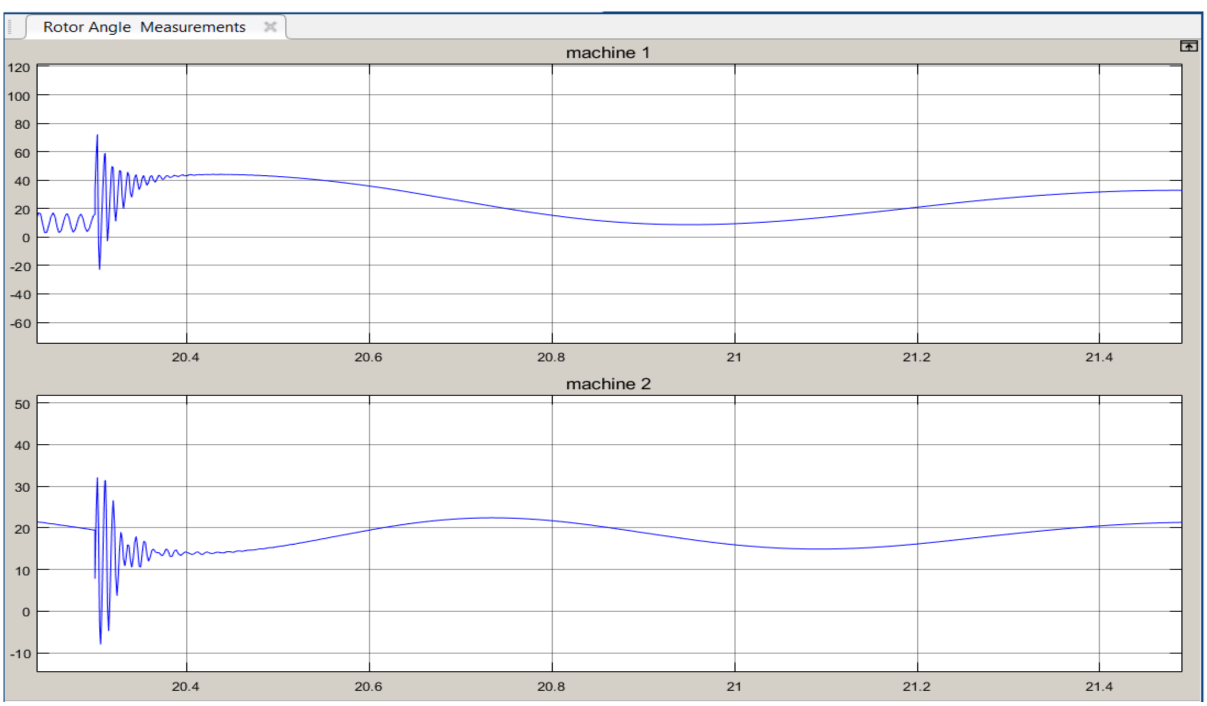

Figure 4.3 Zoomed in view of rotor angle measurement

`

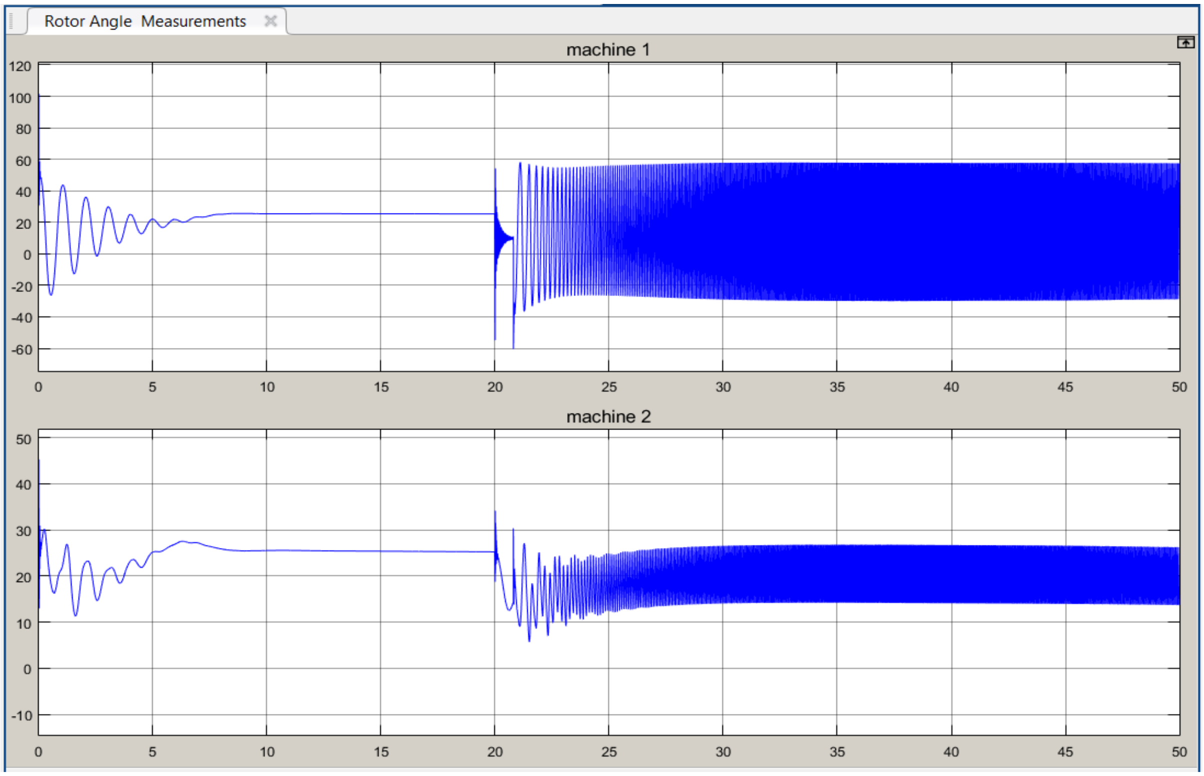

Figure 4.4 Rotor angle curve for an unstable system

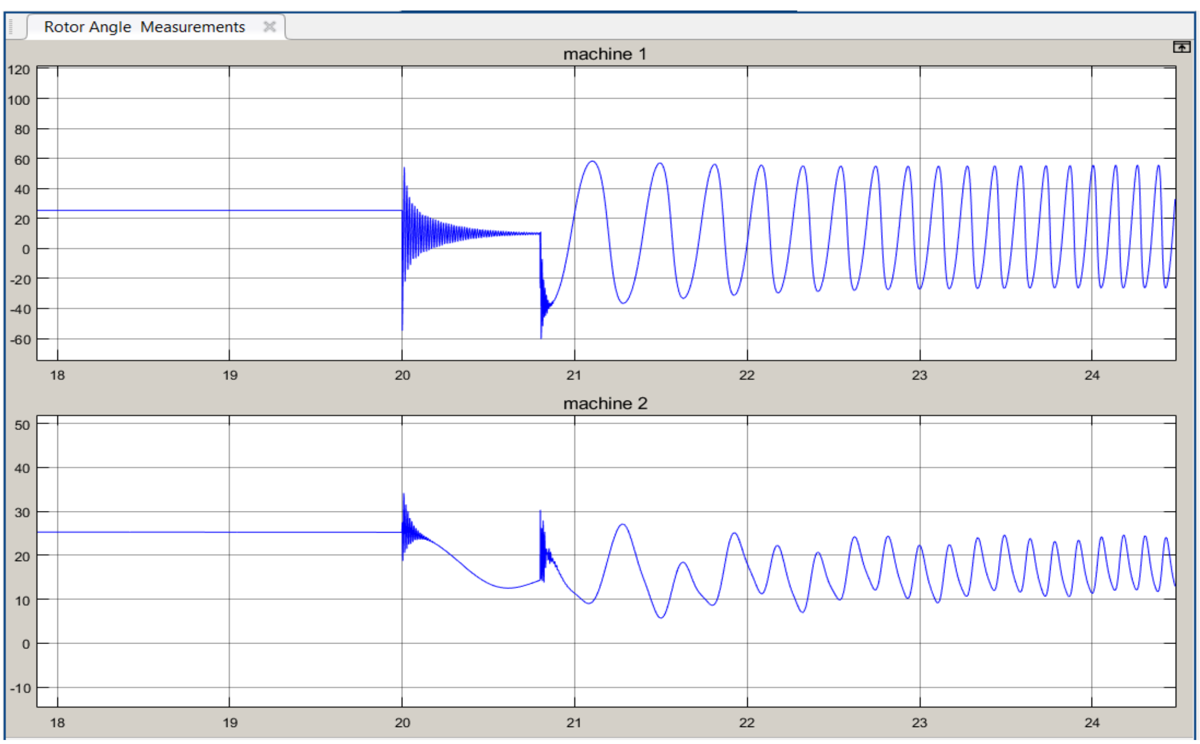

Figure 4.5 Zoomed in view of unstable system

`

4.2 Illustration II

The power system network of an electric utility company is shown in Figure 4.6. The load data and voltage magnitude, generation schedule, and the reactive power limits for the regulated buses are tabulated on the next page. Bus 1, whose voltage is specified as $V_1 = 1.06\measuredangle 0^0$, is taken as the slack bus. The line data containing the series resistance and reactance in per unit, and one-half of the total capacitance in per unit susceptance on a 100-MVA base is also tabulated as shown.

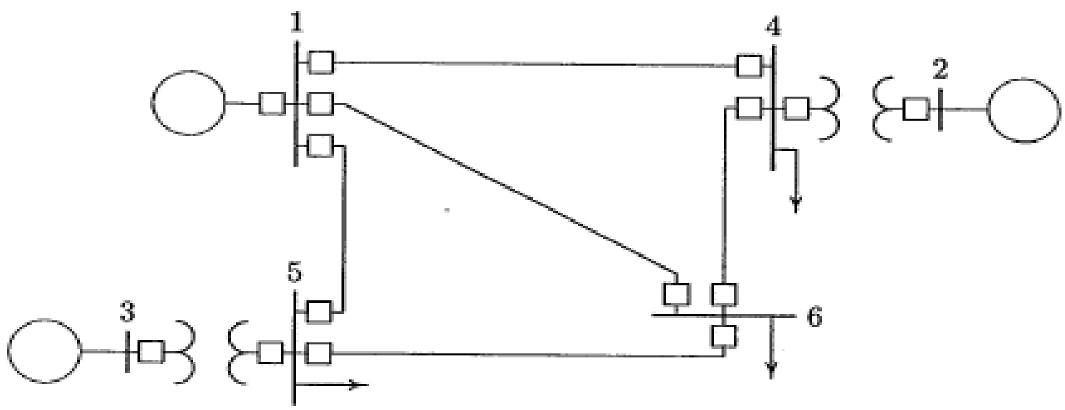

Figure 4.6 Single Line Diagram

Bus No.	Load Data	
	MW	MVar
1	0	0
3	0	0
3	0	0
4	100	70
5	90	30
6	160	110

Table 1 Load Data

`

GENERATION SCHEDULE				
Bus No.	Voltage	Generation (MW)	MVar Limits	
			Max.	Min.
1	1.06			
2	1.04	150	0	140
3	1.03	100	0	90

Table 2 Generation Schedule

Line Data				
Bus No.	Bus No.	R (pu)	X (pu)	½ B (pu)
1	4	0.035	0.225	0.0065
1	5	0.025	0.105	0.0045
1	6	0.04	0.215	0.0055
2	4	0	0.035	0
3	5	0	0.042	0
4	6	0.028	0.125	0.0035
5	6	0.026	0.175	0.03

Table 3 Line Data

The generator's armature reactance and transient reactance in per unit system and the inertia constant in seconds expressed on a 100 MVA base are given as:

MACHINE DATA			
Gen.	R_a	X_d'	H
1	0	0.2	20
2	0	0.15	4
3	0	0.25	5

Table 4 Machine Data

`

A three-phase fault occurs on line 5-6 near bus 6 and is cleared by the simultaneous opening of breakers at both ends of the line. Using the **trstab** program, perform a transient stability analysis. Determine the system stability for (a) When the fault is cleared in 0.4 second (b) When the fault is cleared in 0.5 second (c) Repeat the simulation to determine the critical clearing time.

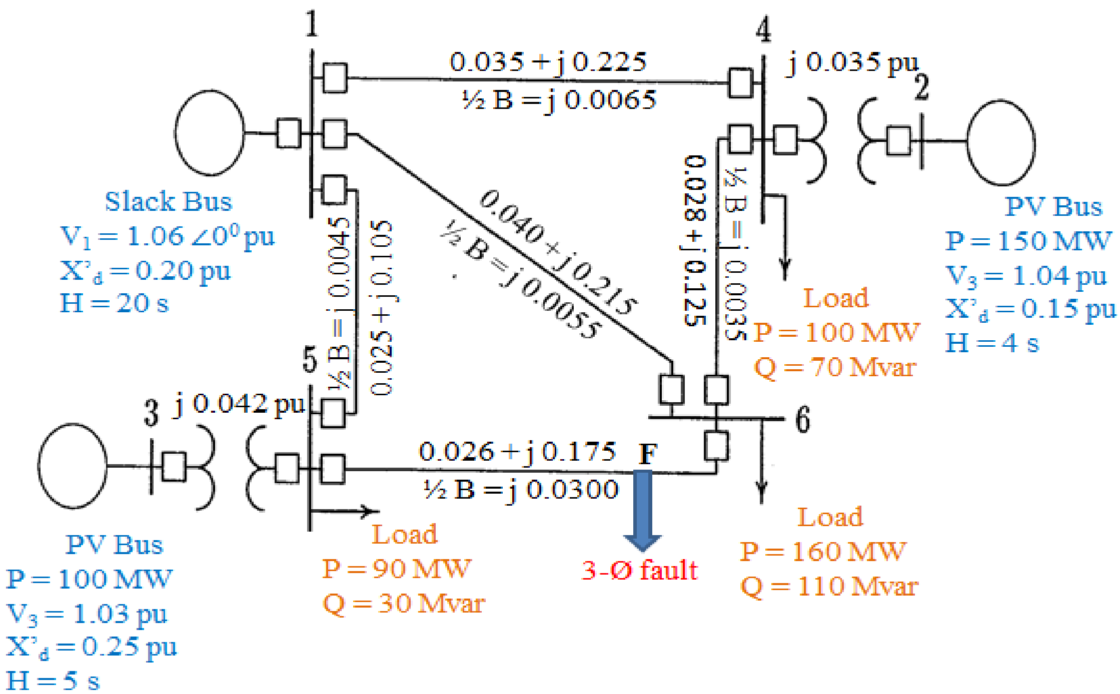

Figure 4.7 Diagram of the power system network with corresponding data

Solution:

Codes: Refer Appendix

Data and Commands

The power flow result is

Power Flow Solution by Newton-Raphson Method

Maximum Power Mismatch = 1.80187e-07

No. of Iterations = 4

`

Bus No.	Voltage Mag.	Angle Degree	------Load------ MW	Mvar	---Generation--- MW	Mvar	Injected Mvar
1	1.060	0.000	0.000	0.000	105.287	107.335	0.000
2	1.040	1.470	0.000	0.000	150.000	99.771	0.000
3	1.030	0.800	0.000	0.000	100.000	35.670	0.000
4	1.008	-1.401	100.000	70.000	0.000	0.000	0.000
5	1.016	-1.499	90.000	30.000	0.000	0.000	0.000
6	0.941	-5.607	160.000	110.000	0.000	0.000	0.000
Total			350.000	210.000	355.287	242.776	0.000

The trstab result is

Prefault reduced bus admittance matrix

Ybf =

0.3517 - 2.8875i   0.2542 + 1.1491i   0.1925 + 0.9856i

0.2542 + 1.1491i   0.5435 - 2.8639i   0.1847 + 0.6904i

0.1925 + 0.9856i   0.1847 + 0.6904i   0.2617 - 2.2835i

G(i)	E'(i)	d0(i)	Pm(i)
1	1.2781	8.9421	1.0529
2	1.2035	11.8260	1.5000
3	1.1427	13.0644	1.0000

`

Enter faulted bus No. -> 6

Faulted reduced bus admittance matrix

Ydf =

```
   0.1913 - 3.5849i   0.0605 + 0.3644i   0.0523 + 0.4821i
   0.0605 + 0.3644i   0.3105 - 3.7467i   0.0173 + 0.1243i
   0.0523 + 0.4821i   0.0173 + 0.1243i   0.1427 - 2.6463i
```

Fault is cleared by opening a line. The bus to bus nos. of the

line to be removed must be entered within brackets, e.g. [5, 7]

Enter the bus to bus Nos. of line to be removed -> [5,6]

Post-fault reduced bus admittance matrix

Yaf =

```
   0.3392 - 2.8879i   0.2622 + 1.1127i   0.1637 + 1.0251i
   0.2622 + 1.1127i   0.6020 - 2.7813i   0.1267 + 0.5401i
   0.1637 + 1.0251i   0.1267 + 0.5401i   0.2859 - 2.0544i
```

Enter clearing time of fault in sec. tc = 0.4

Enter final simulation time in sec. tf = 1.5

Fault is cleared at 0.400 Sec.

The program obtains a plot of the swing curves which is presented in Figure 4.8.

`

Phase angle difference (fault cleared at 0.4 sec)

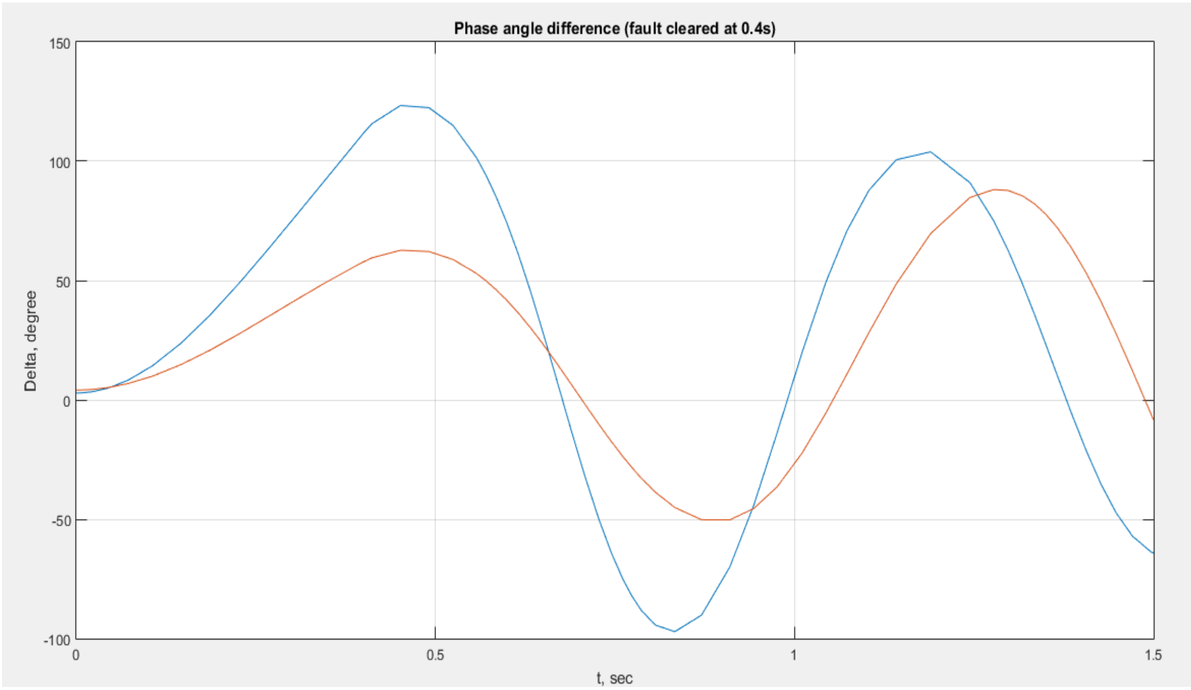

Figure 4.8 Plots of angle differences for machines 2 and 3 of Illistration II

Again, the tabulated result is printed, and plots of the swing curves are obtained as shown in Figure 4.9. Figure 4.8 shows that the phase angle differences, after reaching a maximum of δ_{21} = 123.9° and δ_{31}= 62.95° will decrease, and the machines swing together. Hence, the system is found to be stable when fault is cleared in 0.4 second.

The program inquires for another fault clearing time, and the results continue as follows:

Another clearing time of fault? Enter 'y' or 'n' within quotes -> 'y'

Enter clearing time of fault in sec. tc = 0.5

Enter final simulation time in sec. tf = 1.5

Fault is cleared at 0.500 Sec.

`

The swing curves shown in Figure 4.9 show that machine 2 phase angle increases without limit. Thus, the system is unstable when fault is cleared in 0.5 second.

Phase angle difference (fault cleared at 0.5 sec)

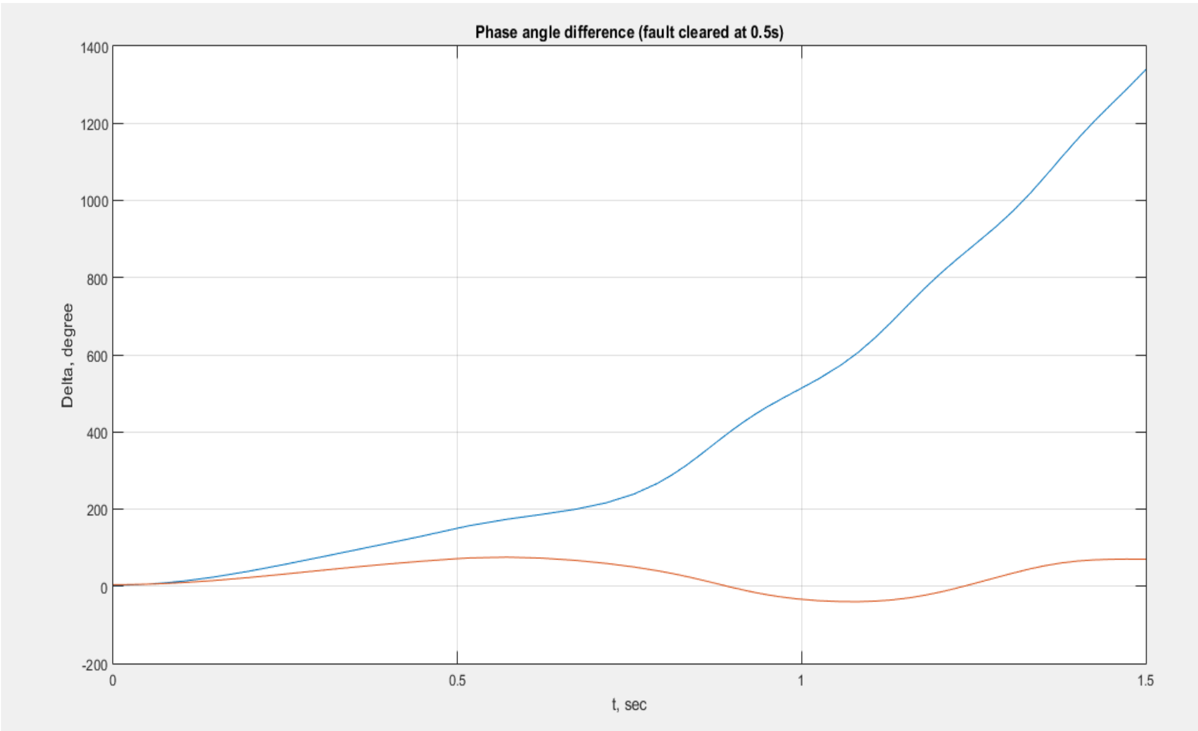

Figure 4.9 Plots of angle differences for machines 2 and 3

The simulation is repeated for a clearing time of 0.45 second, which is found to be critically stable.

Another clearing time of fault? Enter 'y' or 'n' within quotes -> 'y'

Enter clearing time of fault in sec. tc = 0.45

Enter final simulation time in sec. tf = 1.5

Fault is cleared at 0.450 Sec.

`

Phase angle difference (fault cleared at 0.5 sec)

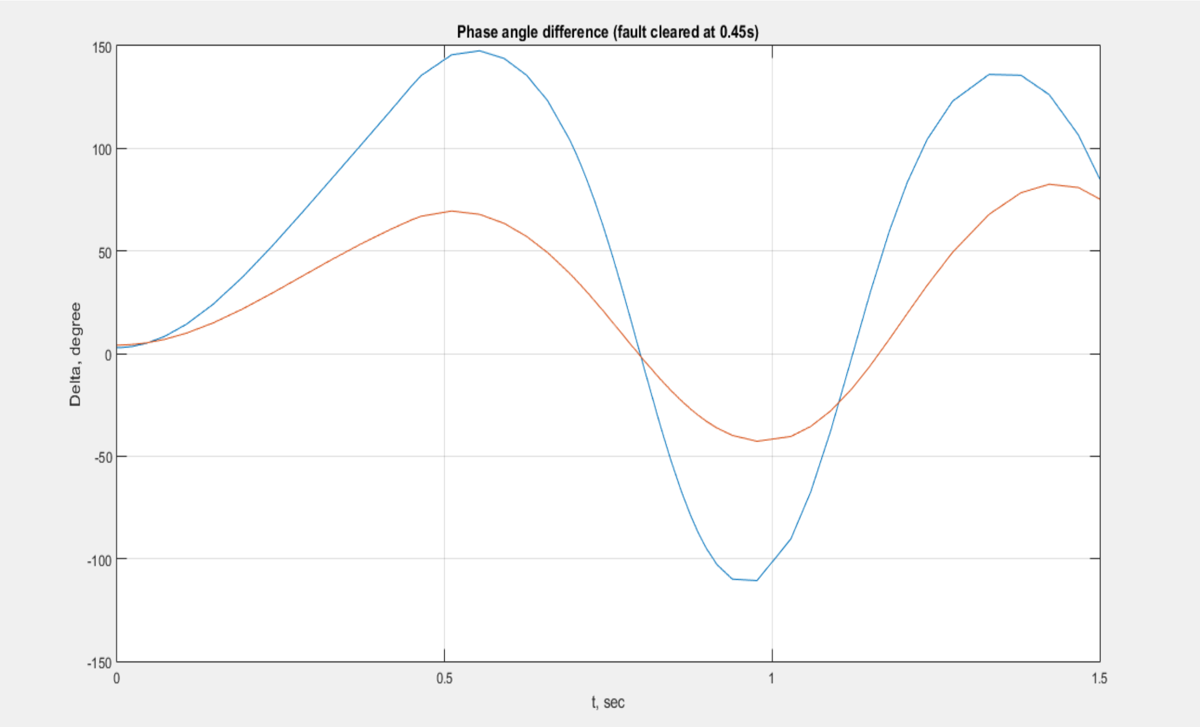

Figure 4.10 Plots of angle differences for machines 2 and 3

These plots of simulation help to determine and confirm the Critical Clearing Time (CCT) for CBs so as to maintain the stability of the power system. For this particular case, the CCT is found to be 0.45 second. Following this result, CBs can be operated at or below the CCT.

`

5 CONCLUSION

A complete study for transient stability of a single machine and multi-machine power system connected to an infinite grid was developed using MATLAB. MATLAB programming and simulation is not only best suited for an analytical study of a power system network, but it can also incorporate several tools for a detailed study and parameter optimization. The program is user friendly, with tremendous interactive capacity. For a transient stability study the program facilitates fast and precise solution of non-linear differential equation viz. the swing equation. The user can easily select and modify the solver type, step sizes, tolerance, simulation period, output options etc. Any parameter can easily be modified through simple MATLAB commands to suit the changes in the original power system network due to a fault.

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. For one-machine system connected to infinite bus it can be seen that an increase in the inertia constant M of the machine reduces the angle through which it swings in a given time interval offering a method of improving stability. But this cannot be employed in practice because of economic reasons and for the reason of slowing down of the response of the speed-governor loop apart from an excessive rotor weight.

Transient Stability Analysis is a major investigation in power systems due to the increasing stress on power system networks. The main goal of this analysis is to gather critical information, such as CCT of the circuit breakers for faults in the system, effect of location of fault within a power system network, effect of load increment on the CCT and effect of fault on the synchronous speed of machines in the system. This information can aid protection engineer make an informed decision when designing protection scheme for a power system. To analyze the effects of these parameters on the system stability, a three-phase fault was applied in the system. The stability of the system has been observed based on the simulation graphs of the generators' swing curves and generators' synchronous speed. The simulation results showed that the critical clearing time decreases as the fault location becomes closer to the power generating station.

`

6 RECOMMENDATIONS

It is clear from the above study that MATLAB offers a wide perspective for programming and analysis of various power system networks. The features of MATLAB are easy to understand and implement. In this project, a single machine connected to an infinite grid and multi-machine system is considered. However, it explains very well the principles and the scope of the tool, typically for the study of the transient stability in a power system. The other factors such as effects of excitation, turbine, speed governor or any control measure, can be easily realized through MATLAB program. Furthermore, the optimization and application of ANN and fuzzy logic can be implemented through MATLAB in transient stability studies.

`

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[6] www.google.com

`

APPENDIX A

A.1 Single Machine Connected to Infinite Bus

Illustration II

```
E = 1.35, V= 1.0; H= 9.94; X=0.65; Pm=0.6; D=0.138; f0 = 60;
Pmax = E*V/X, d0 = asin(Pm/Pmax)              % Max. power
Ps = Pmax*cos(d0)                             % Synchronizing power coefficient
wn = sqrt(pi*60/H*Ps)                         % Undamped frequency of oscillation
z = D/2*sqrt(pi*60/(H*Ps))                    % Damping ratio
wd = wn*sqrt(1-z^2), fd = wd/(2*pi)           %Damped frequency oscillation
tau = 1/(z*wn)                                % Time constant
th = acos(z)                                  % Phase angle theta
Dd0 = 10*pi/180;                              % Initial angle in radian
t = 0:.01:3;
Dd = Dd0/sqrt(1-z^2)*exp(-z*wn*t).*sin(wd*t + th);
d = (d0+Dd)*180/pi;                           % Load angle in degree
Dw = -wn*Dd0/sqrt(1-z^2)*exp(-z*wn*t).*sin(wd*t);
f = f0 + Dw/(2*pi);                           % Frequency in Hz
figure(1), subplot(2,1,1), plot(t, d), grid
xlabel('t,  sec'), ylabel('Delta, degree')
subplot(2,1,2), plot(t,f), grid
xlabel('t, sec'), ylabel('f, Hz')
 A = [0  1; -wn^2  -2*z*wn];                  % wn, z and t are defined earlier
B = [0; 0];                                   % Column B zero-input
C = [1 0; 0 1];                               % Unity matrix defining output y as x1 and x2
D = [0; 0];
Dx0 = [Dd0; 0];                               % Zero initial cond., Dd0 is defined earlier
[y,x]= initial(A, B, C, D, Dx0, t);
```

`

```
Dd = x(:, 1); Dw = x(:, 2);                    % State variables x1 and x2
d = (d0 + Dd)*180/pi;                         % Load angle in degree
f = f0 + Dw/(2*pi);                           % Frequency in Hz
figure(2), subplot(2,1,1), plot(t, d), grid
xlabel('t, sec'), ylabel('Delta, degree')
subplot(2,1,2), plot(t, f), grid
xlabel('t, sec'), ylabel('f, Hz')
subplot(111)
```

`

Illustration III

```
E = 1.35, V= 1.0; H= 9.94; X=0.65; Pm=0.6; D=0.138; f0 = 60;
Pmax = E*V/X, d0 = asin(Pm/Pmax)          % Max. power
Ps = Pmax*cos(d0)                         % Synchronizing power coefficient
wn = sqrt(pi*60/H*Ps)                     % Undamped frequency of of oscillation
z = D/2*sqrt(pi*60/(H*Ps))                % Damping ratio
wd = wn*sqrt(1-z^2), fd = wd/(2*pi)       %Damped frequency oscill.
tau = 1/(z*wn)                            % Time constant
th = acos(z)                              % Phase angle theta
Dp = 0.2; Du = pi*f0/H*Dp;                % Small step change in power input
t = 0:.01:3;
     % Plotting the analytical solution for Illustration-III
Dd = Du/wn^2*(1- 1/sqrt(1-z^2)*exp(-z*wn*t).*sin(wd*t + th));
d = (d0+Dd)*180/pi;                       % Load angle in degrees
Dw = Du/(wn*sqrt(1-z^2))*exp(-z*wn*t).*sin(wd*t);
f = f0 + Dw/(2*pi);                       % Frequency in Hz
figure(1), subplot(2,1,1), plot(t, d), grid
xlabel('t, sec'), ylabel('Delta, degrees')
subplot(2,1,2), plot(t,f), grid
xlabel('t, sec'), ylabel('Frequency, Hz')
A = [0  1; -wn^2  -2*z*wn];               % wn, z and t are defined earlier
Dp = 0.1; Du = pi*f0/H*Dp;                % Small step change in power input
B = [0;1]*Du;
C = [1 0; 0  1];                          % Unity matrix defining output y as x1 and x2
D = [0; 0];
[y, x] = step(A, B, C, D, 1, t);
Dd = x(:, 1); Dw = x(:, 2);               % State variables x1 and x2
d1 = (d0 + Dd)*180/pi;                    % Load angle in degrees
f1 = f0 + Dw/(2*pi);                      % Frequency in Hz
figure(2), subplot(2,1,1), plot(t, d), grid
```

`

```
xlabel('t, sec'), ylabel('Delta, degrees')
subplot(2,1,2), plot(t, f), grid
xlabel('t, sec'), ylabel('Frequency, Hz')
subplot(111)
```

`

Illustration IV

```
% Initial real power P0 = 0.60
P0 = 0.6; E = 1.35; V = 1.0; X = 0.65;
eacpower(P0, E, V, X)
h=figure;
function eacpower(P0, E, V, X)
% This program obtains the power angle curve for a one-machine system
% during normal operation. Using equal area criterion the maximum input
% power that can be suddenly applied for the machine to remain critically
% stable is obtained.
if exist('P0')~=1
P0 = input('Generator initial power in p.u. P0 = '); else, end
if exist('E')~=1
E = input('Generator e.m.f. in p.u. E = '); else, end
if exist('V')~=1
V = input('Infinite bus-bar voltage in p.u. V = '); else, end
if exist('X')~=1
X = input('Reactance between internal emf and infinite bus in p.u. X = '); else, end
Pemax= E*V/X;
if P0 >= Pemax
fprintf('\nP0 must be less than the peak electrical power Pemax = %5.3f p.u. \n', Pemax)
fprintf('Try again. \n\n')
return, end
d0=asin(P0/Pemax);
delta = 0:.01:pi;
Pe = Pemax*sin(delta);
dmax=pi;
Ddmax=1;
while abs(Ddmax) > 0.00001
Df = cos(d0) - (sin(dmax)*(dmax-d0)+cos(dmax));
```

`

```
J=cos(dmax)*(dmax-d0);
Ddmax=Df/J;
dmax=dmax+Ddmax;
end
dc=pi-dmax;
Pm2=Pemax*sin(dc);
Pmx =[0  pi-d0]*180/pi; Pmy=[P0 P0];
Pm2x=[0  dmax]*180/pi; Pm2y=[Pm2 Pm2];
x0=[d0 d0]*180/pi; y0=[0 Pm2]; xc=[dc dc]*180/pi; yc=[0 Pemax*sin(dc)];
xm=[dmax dmax]*180/pi; ym=[0 Pemax*sin(dmax)];
d0=d0*180/pi; dmax=dmax*180/pi; dc=dc*180/pi;
x=(d0:.1:dc);
y=Pemax*sin(x*pi/180);
%y1=Pe2max*sin(d0*pi/180);
%y2=Pe2max*sin(dc*pi/180);
x=[d0 x dc];
y=[Pm2 y Pm2];
xx=dc:.1:dmax;
h=Pemax*sin(xx*pi/180);
xx=[dc xx  dmax];
hh=[Pm2 h  Pm2];
delta=delta*180/pi;
%clc
fprintf('\nInitial power                              =%7.3f p.u.\n', P0)
fprintf('Initial power angle                        =%7.3f degrees \n', d0)
fprintf('Sudden additional power                    =%7.3f p.u.\n', Pm2-P0)
fprintf('Total power for critical stability        =%7.3f p.u.\n', Pm2)
fprintf('Maximum angle swing                         =%7.3f degrees \n', dmax)
fprintf('New operating angle                        =%7.3f degrees \n\n\n', dc)
fill(x,y,'m')
hold;
```

`

```
fill(xx,hh,'c')
plot(delta, Pe,'-', Pmx, Pmy,'g', Pm2x,Pm2y,'g', x0,y0,'c', xc,yc, xm,ym,'r'), grid
Title('Equal-area criterion applied to the sudden change in power')
xlabel('Power angle, degree'), ylabel(' Power, per unit')
axis([0 180  0 1.1*Pemax])
hold off;
```

`

Illustration V (a)

```
function eacfault(Pm, E, V, X1, X2, X3)
% This program obtains the power angle curves for a one-machine system
% before fault, during fault and after the fault clearance.
% The equal area criterion is applied to find the critical clearing angle
% for the machine to stay synchronized to the infinite bus bar
if exist('Pm')~=1
Pm = input('Generator output power in p.u. Pm = '); else, end
if exist('E')~=1
E = input('Generator e.m.f. in p.u. E = '); else, end
if exist('V')~=1
V = input('Infinite bus-bar voltage in p.u. V = '); else, end
if exist('X1')~=1
X1 = input('Reactance before Fault in p.u. X1 = '); else, end
if exist('X2')~=1
X2 = input('Reactance during Fault in p.u. X2 = '); else, end
if exist('X3')~=1
X3 = input('Reactance aftere Fault in p.u. X3 = '); else, end
Pe1max = E*V/X1; Pe2max=E*V/X2; Pe3max=E*V/X3;
delta = 0:.01:pi;
Pe1 = Pe1max*sin(delta); Pe2 = Pe2max*sin(delta); Pe3 = Pe3max*sin(delta);
d0 =asin(Pm/Pe1max); dmax = pi-asin(Pm/Pe3max);
cosdc = (Pm*(dmax-d0)+Pe3max*cos(dmax)-Pe2max*cos(d0))/(Pe3max-Pe2max);
  if abs(cosdc) > 1
  fprintf('No critical clearing angle could be found.\n')
  fprintf('system can remain stable during this disturbance.\n\n')
  return
  else, end
dc=acos(cosdc);
if dc > dmax
```

`

```
fprintf('No critical clearing angle could be found.\n')
  fprintf('System can remain stable during this disturbance.\n\n')
  return
  else, end
Pmx=[0  pi-d0]*180/pi; Pmy=[Pm Pm];
x0=[d0 d0]*180/pi; y0=[0 Pm]; xc=[dc dc]*180/pi; yc=[0 Pe3max*sin(dc)];
xm=[dmax dmax]*180/pi; ym=[0 Pe3max*sin(dmax)];
d0=d0*180/pi; dmax=dmax*180/pi; dc=dc*180/pi;
x=(d0:.1:dc);
y=Pe2max*sin(x*pi/180);
y1=Pe2max*sin(d0*pi/180);
y2=Pe2max*sin(dc*pi/180);
x=[d0 x dc];
y=[Pm y Pm];
xx=dc:.1:dmax;
h=Pe3max*sin(xx*pi/180);
xx=[dc xx  dmax];
hh=[Pm h  Pm];
delta=delta*180/pi;
if X2 == inf
fprintf('\nFor this case tc can be found from analytical formula. \n')
H=input('To find tc enter Inertia Constant H, (or 0 to skip) H = ');
   if H ~= 0
   d0r=d0*pi/180; dcr=dc*pi/180;
   tc = sqrt(2*H*(dcr-d0r)/(pi*60*Pm));
   else, end
else, end
%clc
fprintf('\nInitial power angle     = %7.3f \n', d0)
fprintf('Maximum angle swing     = %7.3f \n', dmax)
fprintf('Critical clearing angle = %7.3f \n\n', dc)
```

`

```
if X2==inf & H~=0
fprintf('Critical clearing time  = %7.3f sec. \n\n', tc)
else, end
h = figure; figure(h);
fill(x,y,'m')
hold;
fill(xx,hh,'c')
plot(delta, Pe1,'-', delta, Pe2,'r-',  delta, Pe3,'g-', Pmx, Pmy,'b-', x0,y0, xc,yc, xm,ym), grid
Title('Application of equal area criterion to a critically cleared system')
xlabel('Power angle, degree'), ylabel(' Power, per unit')
text(5, 1.07*Pm, 'Pm')
text(50, 1.05*Pe1max,['Critical clearing angle = ',num2str(dc)])
axis([0 180  0 1.1*Pe1max])
hold off;
```

`

Illustration V (b)

```
function eacfault(Pm, E, V, X1, X2, X3)
% This program obtains the power angle curves for a one-machine system
% before fault, during fault and after the fault clearance.
% The equal area criterion is applied to find the critical clearing angle
% for the machine to stay synchronized to the infinite bus bar
if exist('Pm')~=1
Pm = input('Generator output power in p.u. Pm = '); else, end
if exist('E')~=1
E = input('Generator e.m.f. in p.u. E = '); else, end
if exist('V')~=1
V = input('Infinite bus-bar voltage in p.u. V = '); else, end
if exist('X1')~=1
X1 = input('Reactance before Fault in p.u. X1 = '); else, end
if exist('X2')~=1
X2 = input('Reactance during Fault in p.u. X2 = '); else, end
if exist('X3')~=1
X3 = input('Reactance aftere Fault in p.u. X3 = '); else, end
Pe1max = E*V/X1; Pe2max=E*V/X2; Pe3max=E*V/X3;
delta = 0:.01:pi;
Pe1 = Pe1max*sin(delta); Pe2 = Pe2max*sin(delta); Pe3 = Pe3max*sin(delta);
d0 =asin(Pm/Pe1max); dmax = pi-asin(Pm/Pe3max);
cosdc = (Pm*(dmax-d0)+Pe3max*cos(dmax)-Pe2max*cos(d0))/(Pe3max-Pe2max);
  if abs(cosdc) > 1
  fprintf('No critical clearing angle could be found.\n')
  fprintf('system can remain stable during this disturbance.\n\n')
  return
  else, end
dc=acos(cosdc);
if dc > dmax
```

`

```
fprintf('No critical clearing angle could be found.\n')
  fprintf('System can remain stable during this disturbance.\n\n')
  return
  else, end
Pmx=[0  pi-d0]*180/pi; Pmy=[Pm Pm];
x0=[d0 d0]*180/pi; y0=[0 Pm]; xc=[dc dc]*180/pi; yc=[0 Pe3max*sin(dc)];
xm=[dmax dmax]*180/pi; ym=[0 Pe3max*sin(dmax)];
d0=d0*180/pi; dmax=dmax*180/pi; dc=dc*180/pi;
x=(d0:.1:dc);
y=Pe2max*sin(x*pi/180);
y1=Pe2max*sin(d0*pi/180);
y2=Pe2max*sin(dc*pi/180);
x=[d0 x dc];
y=[Pm y Pm];
xx=dc:.1:dmax;
h=Pe3max*sin(xx*pi/180);
xx=[dc xx  dmax];
hh=[Pm h  Pm];
delta=delta*180/pi;
if X2 == inf
fprintf('\nFor this case tc can be found from analytical formula. \n')
H=input('To find tc enter Inertia Constant H, (or 0 to skip) H = ');
   if H ~= 0
   d0r=d0*pi/180; dcr=dc*pi/180;
   tc = sqrt(2*H*(dcr-d0r)/(pi*60*Pm));
   else, end
else, end
%clc
fprintf('\nInitial power angle     = %7.3f \n', d0)
fprintf('Maximum angle swing     = %7.3f \n', dmax)
fprintf('Critical clearing angle = %7.3f \n\n', dc)
```

`

```
if X2==inf & H~=0
fprintf('Critical clearing time  = %7.3f sec. \n\n', tc)
else, end
h = figure; figure(h);
fill(x,y,'m')
hold;
fill(xx,hh,'c')
plot(delta, Pe1,'-', delta, Pe2,'r-',  delta, Pe3,'g-', Pmx, Pmy,'b-', x0,y0, xc,yc, xm,ym), grid
Title('Application of equal area criterion to a critically cleared system')
xlabel('Power angle, degree'), ylabel(' Power, per unit')
text(5, 1.07*Pm, 'Pm')
text(50, 1.05*Pe1max,['Critical clearing angle = ',num2str(dc)])
axis([0 180  0 1.1*Pe1max])
hold off;
```

`

A.2 Multi-Machine System

Illustration II

```
% Transient stability analysis of a multimachine power system network
% Program ``trstab" must be used in conjuntion with the power flow
% program. Any of the power flow programs ``lfgauss", ``lfnewton",
% ``decoupled" or ``perturb" can be used prior to ``trstab" program.
% Power flow program provide the power, voltage magnitude and phase
% angle for each bus. Also, the load admittances are returned in a
% matrix named ``yload".  In addition to the required power flow data,
% Transient reactance, and inertia constant of each machine must be
% specified.  This is defined in a matrix named ``gendata", Each row
% contain the bus No. to which a generator is connected, armature
% resistance, transient reactance, and the machine inertia constant.
% Program ``trstab" obtains the prefault bus admittance matrix including
% the load admittances. Voltage behind transient reactance are obtained.
% The reduced admittance matrix before, during and after fault are found.
% Machine equations are expressed in state variable form and the MATLAB
% ode23 is used to solve the multimachine equations. The phase angle
% difference of each machine with respect to the slack bus are plotted.
% The simulation can be repeated for a different fault clearing time, or
% a different fault location.
 global Pm f H E  Y th ngg
f=60;
%zdd=gendata(:,2)+j*gendata(:,3);
ngr=gendata(:,1);
%H=gendata(:,4);
ngg=length(gendata(:,1));
%%
```

`

```
for k=1:ngg
zdd(ngr(k))=gendata(k, 2)+j*gendata(k,3);
%H(ngr(k))=gendata(k, 4);
H(k)=gendata(k,4);   % new
end
%%
for k=1:ngg
I=conj(S(ngr(k)))/conj(V(ngr(k)));
%Ep(ngr(k)) = V(ngr(k))+zdd(ngr(k))*I;
%Pm(ngr(k))=real(S(ngr(k)));
Ep(k) = V(ngr(k))+zdd(ngr(k))*I;  % new
Pm(k)=real(S(ngr(k)));            % new
 end
E=abs(Ep); d0=angle(Ep);
for k=1:ngg
nl(nbr+k) = nbus+k;
 nr(nbr+k) = gendata(k, 1);
 %R(nbr+k)  = gendata(k, 2);
%X(nbr+k)  = gendata(k, 3);
R(nbr+k)  = real(zdd(ngr(k)));
X(nbr+k)  = imag(zdd(ngr(k)));
 Bc(nbr+k)  = 0;
a(nbr+k) = 1.0;
yload(nbus+k)=0;
end
nbr1=nbr; nbus1=nbus;
nbrt=nbr+ngg;
nbust=nbus+ngg;
linedata=[nl, nr, R, X, -j*Bc, a];
[Ybus, Ybf]=ybusbf(linedata, yload, nbus1,nbust);
fprintf('\nPrefault reduced bus admittance matrix \n')
```

`

```
Ybf
Y=abs(Ybf); th=angle(Ybf);
Pm=zeros(1, ngg);
disp(['     G(i)    E''(i)     d0(i)       Pm(i)'])
for ii = 1:ngg
for jj = 1:ngg
Pm(ii) = Pm(ii) + E(ii)*E(jj)*Y(ii, jj)*cos(th(ii, jj)-d0(ii)+d0(jj));
 end,
fprintf('       %g', ngr(ii)), fprintf('   %8.4f',E(ii)), fprintf('   %8.4f', 180/pi*d0(ii))
fprintf('  %8.4f \n',Pm(ii))
end
respfl='y';
while respfl =='y' | respfl=='Y'
nf=input('Enter faulted bus No. -> ');
fprintf('\nFaulted reduced bus admittance matrix\n')
Ydf=ybusdf(Ybus, nbus1, nbust, nf)
%Fault cleared
[Yaf]=ybusaf(linedata, yload, nbus1,nbust, nbrt);
fprintf('\nPostfault reduced bus admittance matrix\n')
Yaf
resptc='y';
while resptc =='y' | resptc=='Y'
tc=input('Enter clearing time of fault in sec. tc = ');
tf=input('Enter final simulation time in sec.  tf = ');
clear t  x  del
t0 = 0;
w0=zeros(1, length(d0));
x0 = [d0,  w0];
tol=0.0001;
Y=abs(Ydf); th=angle(Ydf);
%[t1, xf] =ode23('dfpek', t0, tc, x0, tol);  % Solution during fault (use with MATLAB 4)
```

`

```
tspan=[t0, tc];                              %use with MATAB 5
[t1, xf] =ode23('dfpek', tspan, x0);  % Solution during fault (use with MATLAB 5)
x0c =xf(length(xf), :);
Y=abs(Yaf); th=angle(Yaf);
%[t2,xc] =ode23('afpek', tc, tf, x0c, tol); % Postfault solution (use with MATLAB 4)
tspan = [tc, tf];                        % use with MATLAB 5
[t2,xc] =ode23('afpek', tspan, x0c);        % Postfault solution (use with MATLAB 5)
t =[t1; t2]; x = [xf; xc];
fprintf('\nFault is cleared at %4.3f Sec. \n', tc)
for k=1:nbus
   if kb(k)==1
   ms=k; else, end
end
fprintf('\nPhase angle difference of each machine \n')
fprintf('with respect to the slack in degree.\n')
fprintf('   t - sec')
kk=0;
for k=1:ngg
   if k~=ms
   kk=kk+1;
   del(:,kk)=180/pi*(x(:,k)-x(:,ms));
   fprintf('    d(%g,',ngr(k)), fprintf('%g)', ngr(ms))
   else, end
end
fprintf(' \n')
disp([t, del])
h=figure; figure(h)
plot(t, del)
title(['Phase angle difference (fault cleared at ', num2str(tc),'s)'])
xlabel('t, sec'), ylabel('Delta, degree'), grid
  resp=0;
```

`

```
  while strcmp(resp, 'n')~=1 & strcmp(resp, 'N')~=1 & strcmp(resp, 'y')~=1 & strcmp(resp,
'Y')~=1
  resp=input('Another clearing time of fault? Enter "y" or "n" within quotes -> ');

  if strcmp(resp, 'n')~=1 & strcmp(resp, 'N')~=1 & strcmp(resp, 'y')~=1 & strcmp(resp,
'Y')~=1
  fprintf('\n Incorrect reply, try again \n\n'), end
  end
resptc=resp;
 end
   resp2=0;
   while strcmp(resp2, 'n')~=1 & strcmp(resp2, 'N')~=1 & strcmp(resp2, 'y')~=1 &
strcmp(resp2, 'Y')~=1
   resp2=input('Another fault location: Enter "y" or "n" within quotes -> ');
   if strcmp(resp2, 'n')~=1 & strcmp(resp2, 'N')~=1 & strcmp(resp2, 'y')~=1 & strcmp(resp2,
'Y')~=1
   fprintf('\n Incorrect reply, try again \n\n'), end
   respf1=resp2;
   end
   if respf1=='n' | respf1=='N', return, else, end
end
basemva = 100;  accuracy = 0.0001;  maxiter = 10;
%       Bus Bus Volt Angle      Load          Generator       Injected
%       n0. code mag. deg.  MW      MVar     MW       MVar  Qmin Qmax MVar
busdata=[1  1  1.06   0.0  00.00    00.00    0.00    00.00    0     0   0
         2  2  1.04   0.0  00.00    00.00  150.00    00.00    0   140   0
         3  2  1.03   0.0  00.00    00.00  100.00    00.00    0    90   0
         4  0  1.0    0.0 100.00    70.00   00.00    00.00    0    0    0
         5  0  1.0    0.0  90.00    30.00   00.00    00.00    0    0    0
         6  0  1.0    0.0 160.00   110.00   00.00    00.00    0    0    0];
% Line data
```

`

```
%       Bus Bus  R      X       1/B     1 for line code or
%        no. no. pu     pu       pu     tap setting value
linedata=[1  4  0.035   0.225   0.0065   1.0
          1  5  0.025   0.105   0.0045   1.0
          1  6  0.040   0.215   0.0055   1.0
          2  4  0.000   0.035   0.0000   1.0
          3  5  0.000   0.042   0.0000   1.0
          4  6  0.028   0.125   0.0035   1.0
          5  6  0.026   0.175   0.0300   1.0];

lfybus       % form the bus admittance matrix for power flow
lfnewton     % Power flow solution by Newton-Raphson method
busout       % Prints the power flow solution on the screen
% Generator data
%        Gen.  Ra   Xd'    H
gendata=[ 1     0   0.20   20
          2     0   0.15    4
          3     0   0.25    5];
trstab % Performs the stability analysis
       % User is prompted to enter the clearing time of fault
```