A TOOLBOX FOR STEADY STATE AND TRANSIENT STABILITY ANALYSIS WITH MATLAB

RANDEL ANAK DANA

This thesis is submitted as partial fulfillment of the requirements for the award of the
Bachelor of Electrical Engineering (Control and Instrumentation)

UNIVERSITI MALAYSIA PAHANG

"I hereby acknowledge that the scope and quality of this thesis is qualified for the award of the Bachelor Degree of Electrical Engineering (Control and Instrumentation)"

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Date : 29 NOVEMBER 2007

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Signature : ______________________________

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Date : 29 NOVEMBER 2007

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ABSTRACT

The tendency of a power system to develop restoring forces equal or greater than the disturbing forces to maintain the state of equilibrium is known as stability. The stability problem is concerned with the behavior of the synchronous machines after a disturbance. Stability problems are divided into two major categories which is steady state stability and transient stability. In this project, the analysis will be on steady state and transient stability. The analysis of steady state is important to determine the ability of the power system to regain synchronism after small and slow disturbances. Analysis of transient stability is needed to ensure that the system can withstand the transient condition following a major disturbance. However, the manual calculation using calculator and formula and also the simulation of the steady state stability and transient stability maybe take a long time for student to understand the theory part of stability.The existence of transient and steady state toolbox will help us to create faster transient and steady state analysis. The availability of steady state and transient stability analysis toolbox package has extended classroom capabilities and enhanced student interest in power engineering courses.Therefore, a toolbox for steady state and transient stability analysis is developed.

ABSTRAK

Kecenderungan sesebuah sistem kuasa untuk menghasilkan daya pemulihan bersamaan atau lebih besar daripada daya gangguan bagi mengekalkan keadaan yang seimbang dikenali sebagai kestabilan.Masalah kestabilan adalah berkaitan dengan mesin segerak selepas suatu gangguan.Masalah kestabilan dibahgikan kepada dua kategori utama iaitu kestabilan keadaan mantap dan kestabilan fana.Analisis bagi kestabilan keadaan mantap adalah penting bagi menentukan kebolehan sistem kuasa untuk mendapatkan kesegerakan selepas gangguan yang kecil dan perlahan.Analisis bagi kestabilan fana diperlukan bagi memastikan sistem boleh menghadapi keadaan fana selepas gangguan yang besar.Namun, pengiraan manual menggunakan kalkulator dan formula serta simulasi untuk kestabilan keadaan mantap dan kestabilan fana mengambil masa yang lama untuk pelajar memahami bahagian teori dalam kestabilan.Kewujudan perisian untuk kestabilan fana dan kestabilan keadaan mantap akan membantu membuat analisis tentang kestabilan fana dan kestabilan keadaan mantap dengan lebih cepat.Kewujudan pakej perisian analisis untuk kestabilan keadaan mantap dan kestabilan fana telah membantu meluaskan keupayaan kelas dan meningkatkan minat pelajar dalam kursus kejuruteraan kuasa.Oleh itu, satu perisian untuk analisa kestabilan keadaan mantap dan kestabilan fana telah dibangunkan.

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LIST OF SYMBOLS

D - Damping Power Coefficient

E - Excitation Voltage

f_0 - Frequency

H - Inertia Constant

M - Angular Momentum

Pm - Real Power

Po - Initial Power

tc - Clearing Fault Time

tf - Final Simulation Time

V - Infinite Bus Voltage

X - Transfer Reactance

X1 - Transfer Reactance Before Fault

X2 - Transfer Reactance During Fault

X3 - Transfer Reactance After Fault

X’d - Transient Reactance

Greek Symbol

$\Delta \delta$ - Angle Difference

δ - Angle

δo - Initial Power Angle

δc - Critical Clearing Angle

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CHAPTER 1

INTRODUCTION

1.1 Introduction

The power system stability of generators and loads into large integrated systems is the ability to return to stable or normal operation after having endured some form of disturbance.The study of stability is important because the main requirement of a reliable operation of power system is to keep the synchronous generators running in parallel and with enough capacity to meet the load demand.When synchronous machine are in parallel, they must operate in synchronism.If a generator increase the speed and the rotor advances beyond a critical angle which is between rotor axis and system voltage phasor,the magnetic coupling fails and the generator loses its synchronism and this has cause stability problem[3].

There are two forms of instability in power systems which are the loss of synchronism between synchronous machines and the stalling of asynchronous loads.The system is considered stable if the system settles in a finite time to a new steady- state condition or the oscillatory response of a power system during the transient report is damped.The stability problem can be divided into two kinds which are steady state stability or transient stability.Steady state stability is basically the ability of the power system when operating under given load conditions to retain synchronism when subjected to small disturbances such as the continual changes in load or generation.Transient stability is concerned with sudden and large changes in the network condition such as sudden and large faults.[9]

The analysis of steady state is important to determine the ability of the power system to regain synchronism after small and slow disturbances. Analysis of transient stability is needed to ensure that the system can withstand the transient condition following a major disturbance. However, the manual calculation using calculator and formula and also the simulation of the steady state stability and transient stability maybe take a long time for student to understand the theory part of stability.The existence of transient and steady state toolbox will help us to create faster transient and steady state analysis. The availability of steady state and transient stability analysis toolbox package has extended classroom capabilities and enhanced student interest in power engineering courses.Therefore, a toolbox for steady state and transient stability analysis is developed.

1.2 Project Objective

In this project, the author tried to achieve 3 objectives of this project.

Therefore, the objective of this project is to:

i. To study and analyze the effect of small and large disturbances or fault occurrence on the power system.

ii. To obtain the simulation of steady state and transient stability studies using MATLAB.

iii. To build a user friendly software package using MATLAB GUI for education and training of steady state and transient stability studies.

1.3 Scope of Project

In this project, there are several scopes that the author needs to propose:

i. Analysis and Simulation of transient and steady state stability is done using MATLAB

ii. Toolbox for transient and steady state stability studies is developed using MATLAB GUI.

CHAPTER 2

LITERATURE REVIEW

This chapter will describe the theory of stability, theory of steady state stability, theory of transient stability, MATLAB with Power System Analysis Toolbox, MATLAB Graphical User Interface (GUI), the similar software in market. All of this information is taken from the combined resources which are journals and books.

2.1 Introduction

Literature reviews is needed to determine the method and process in doing the user friendly software package for education and training of steady state and transient stability studies so that the author know what the other researchers had already done in the software package.Journals and articles from IEEE had been used to look for the method to build the user friendly software package and understand the concept of other software package that had been used for education and training of steady state and transient stability studies.

2.2 Theory On Stability Study

The stability of a system of interconnected dynamic components is its stability to return to normal or stable operation after having subjected to some form of disturbance. There are two forms of instability in power systems which are the steady state stability and transient stability. Steady state stability refers to the ability of the power system to retain synchronism when subject to small disturbances such as the continual changes in load or generation. [1] Transient stability is concerned with sudden and large changes in the network conditions such as those brought about by faults. [1]

2.3 Theory On Steady State Stability

Steady state stability refers to the ability of the power system to retain synchronism when subject to small disturbances such as the continual changes in load or generation [1].The power system forms a group of interconnected electromechanical elements where the motions of which may be represented by the appropriate differential equations.This equations may be linearized when in steady state stability where the solution of the differential equation of the motion is in the form of $\delta=k_1e^{a1t} + k_1e^{a1t} +\ldots+ k_1e^{a1t}$ where k1,k2…kn are constants of integration and a1,a2,an are the roots of the characteristic equation obtained through eigenvalue analysis[2] .This differential equation is called characteristic equation of the system where we can determine the behaviour in a linear system.If any of the roots have positive real terms then the quantity δ increases continously with time and the original steady state is not reestablished. The criterion for stability is therefore that all real part of the roots of the characteristic equation be negative; imaginary parts indicate the presence of oscillation.

The determination of roots is readily obtained using eigenvalue analysis package but there is an indirect methods for predicting stability using the Hurwitz-Routh criterion in which stability is predicted without solving the characteristic equation. There is no information regarding the degree of stability or instability is obtained but we can know that the system is stable or not.

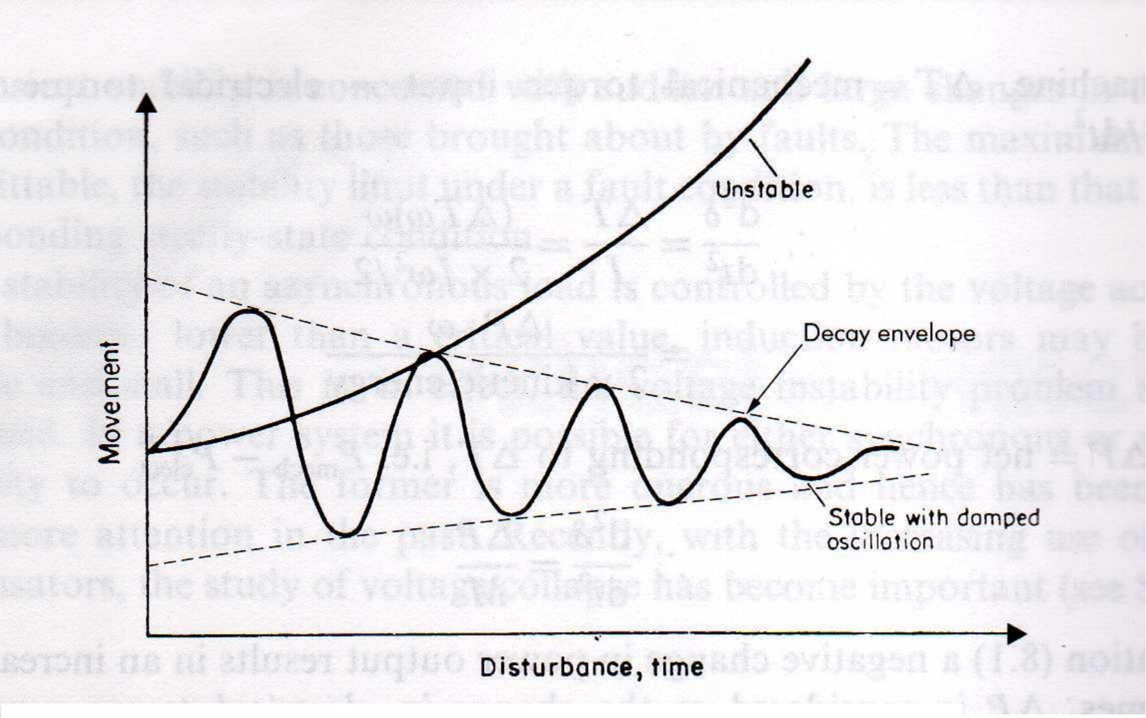


Figure 2.1: Types of response to a disturbance on a system [2]

For a generator connected to an infinite busbar through a network of zero resistance it has been shown that P =(EV/X) sin δ. With operation at Po and δo, we can write

$$M\left(\frac{d^2\triangle\delta}{dt^2}\right) = -\triangle\delta\left(\frac{\eth P}{\eth\delta}\right) \qquad (1)$$

where change in P causeing increase in δ is positive and refers to a small changes in load angle δ such that linearity may be assumed.

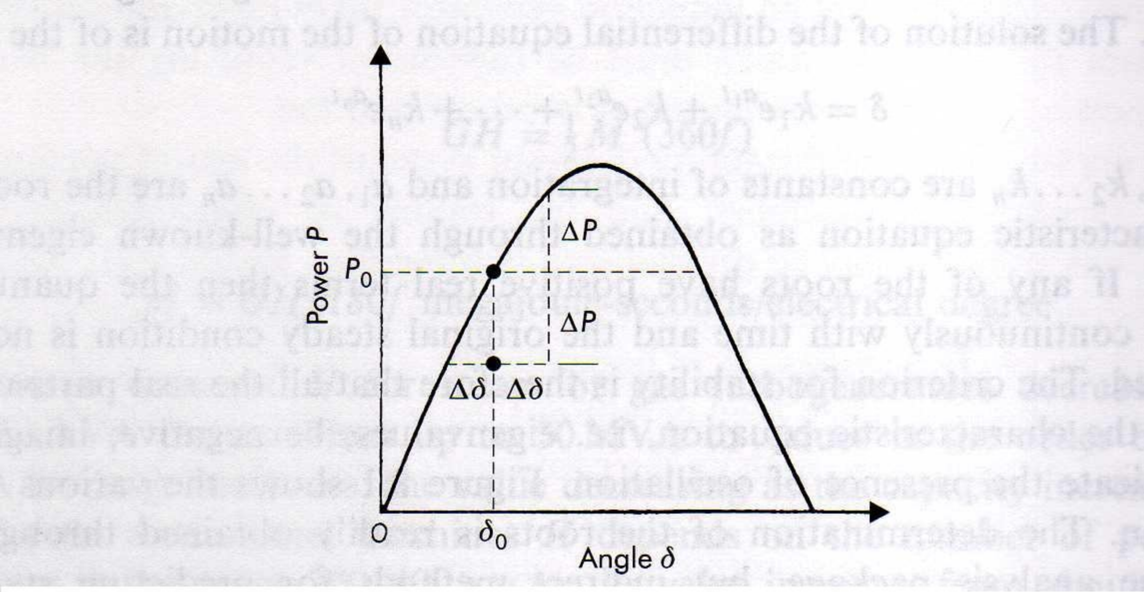


Figure 2.2: Small disturbance –initial operation on power angle curve at Po, δ0. Linear movement assumed about Po, δo [2]

Therefore, $Ms^2\triangle\delta + (\delta P/\delta\eth)\triangle\delta = 0 \qquad (2)$

where s=d/dt

Here, $Ms^2 + (\delta P/\delta\eth) = 0$ is the characteristic equations where it has 2 roots

$$\pm(-(\delta P/\delta\eth))^{1/2} \qquad (3)$$

When $(\delta P/\delta\eth)$ is positive, both roots are imaginary and the motion is oscillatory and undamped. When $(\delta P/\delta\eth)$ is negative, both roots are real and postive and negative , respectively and stability is lost. At $\delta = 90°$, $(\delta P/ \delta ð) = 0$, and the system is at the limit. If damping is accounted for , the equation will become

$$Ms^2\triangle \delta + (\delta P/\delta ð) \triangle \delta + Kds \triangle \delta = 0 \tag{4}$$

and the characteristic equation is

$$Ms^2 + Kd\, s + (\delta P/ \delta ð) = 0 \tag{5}$$

where Kd is the damping coefficient, assumed to be constant, independent of δ.
When $(\delta P/ \delta ð)$ is negative, stability is lost.

The steady state stability limit is the maximum power that can be transmitted in a network between sources and loads when the system is subject to small disturbances.The power system is constantly subjected to small changes as load variations occur. The generator excitations are adjusted to maintain constant terminal voltages and a load flow is carried out after each increment in order to obtain the limiting value of power small increments of load are added to the system.

The simplest criterion for steady state synchronous stability is $(\delta P/\delta ð) > 0$. The use of this criterion involves the following assumptions [7]:

1. Generators are represented by constant impedances in series with the no load voltages
2. The input torques form the turbines are constant.
3. changes in speed are ignored
4. electromagnetic damping in the generators is ignored
5. the changes in load angle δ are small

For calculations made without the aid of computers, it is usual to reduce the network to the simplest form that will keep intact the generator nodes. The value of load angle, power and voltage are then calculated for the given conditions, $\delta P/\delta ð$ determined for each machine and if it is positive, the loading is increased and the process repeated.

2.4 Theory On Transient Stability

Transient stability is concerned with the effect of large disturbances, which are usually due to faults, the most severe of which is a three phase short-circuit and the most frequent is the single-line-to-ground fault [3].The transient stability of a power system is a function of the type and location of the disturbance to which the system is subjected. For example, if two sections of a system are connected by a pair of lines, one of which is switched out, the power-angle characteristic is changed, having a lower peak.The balance between the mechanical and electrical powers is disturbed which causes transient stability problems [3].One of the purposes of the analysis of the system transient stability is to determine a stability limit, usually in terms of a critical fault clearance or autoreclosing time t_{cr} [3].

When a fault occurs at the terminals of a synchronous generator the power output of the machine is greatly reduced as it is supplying a mainly inductive circuit. However, the input power to the generator from the turbine does not have the time to change during the short period of the fault and the rotor had to gain speed to store the excess energy. If the fault is long enough, the rotor angle will increase continously and the synchronism will be lost. Therefore, the time of operation of the protection and circuit breakers is important where the use of autoreclosing circuit breakers is needed.

The autoreclosing circuit breakers open when fault is detected and automatically reclose after a prescibed period (usually less than 1 seconds) [7]. If the fault continues, the circuit breaker reopens and recloses but when fault still continues then breaker remains open.The length of the autoreclose operation must be considered when evaluating the transient stability limits where analysis must include the movement of the rotor during this period.

$$(2(d\delta/dt))(d^2\delta/dt^2) = d/dt\,(d\delta/dt)^2 = (2\,\Delta P/M)(d\delta/dt) \tag{6}$$

$$(d\delta/dt)^2 = 2/M \int \Delta P\, d\delta \tag{7}$$

The integral of $\Delta P\, d\delta$ represents an area on the P- δ diagram.Therefore, the criterion for stability which is called equal area criterion is that the area between the P- δ curve and the line representing power input must be zero.

A simple example of the equal area criterion is by an examination of the switching out of one of two parallel lines which connect a generator to an infinite bus bar.

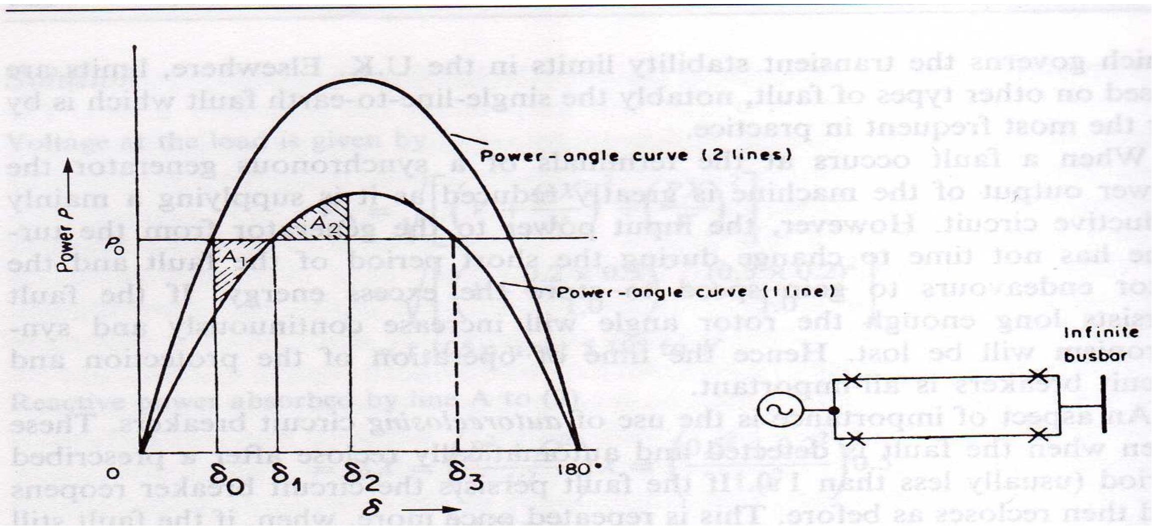


Figure 2.3: Power angle curves for one line and two lines in parallel which shows the equal area criterion with resistance neglected.[2]

For stability to be retained, the two shaded areas (A1 and A 2) are equal and the rotor comes initially to rest at angle δ2, after which it oscillates until completely damped. The initial operating power and angle could be increased to any values that the shaded area between δ0 and δ1 (A1) could be equal to the area between δ1 and δ3 where δ3 = 180- δ1 and this would be the condition for maximum power input.

The power angle curve that produced when there is a fault on one of two parallel lines are shown in Figure 2.4.

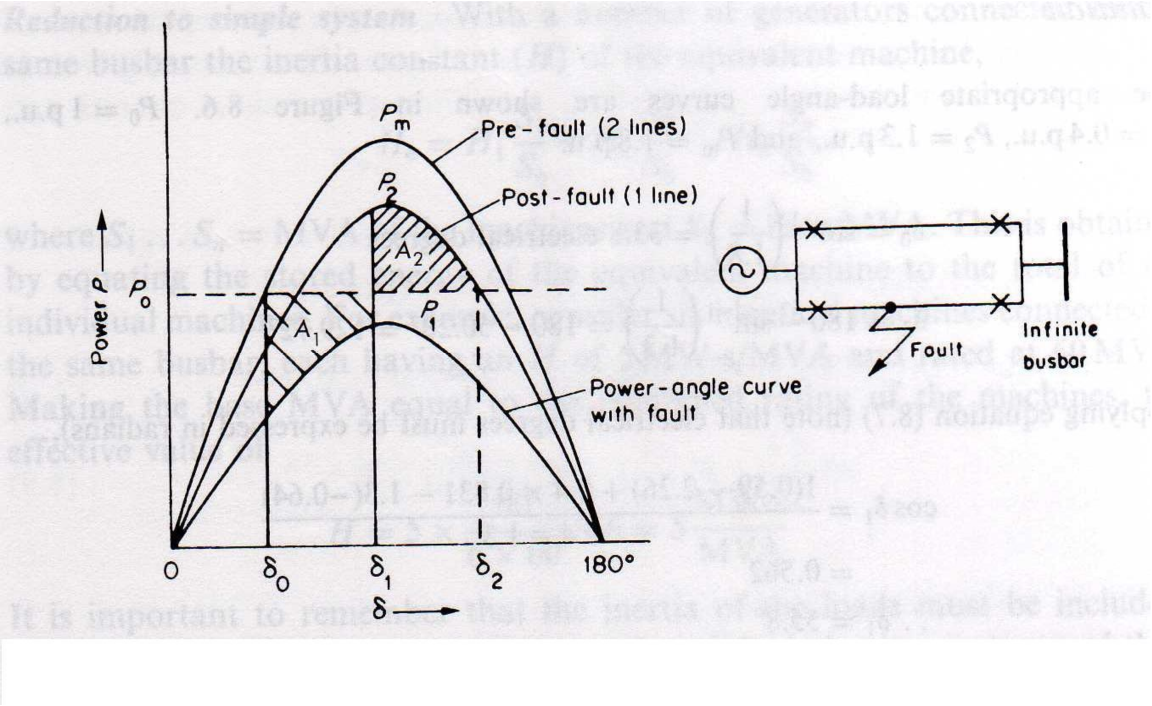


Figure 2.4: The equal area criterion when fault happens on one line of two lines in parallel.[2]

The fault is cleared in a time shown by δ1 and the shaded area δ0 to δ1 (A1) indicates the energy stored. The rotor swings until it reaches δ2 when the two areas A1 and A2 are equal. Po is the maximum operating power for a fault clearance time corresponding to δ1 and δ1 is the critical clearing angle for Po. Critical conditions are reached when $\delta 2 = 180 - \sin^{-1}$ (Po/P2). The time corresponding to the critical clearing angle is known as critical clearing time for the particular value of the power input.

2.5 Matlab With Power System Toolbox Command

In order to perform power system stability analysis in the MATLAB environment, the following variables must be defined;

cctime	Obtains the critical clearing time for fault
eacfault(P0, E,V,X1,X2,X3)	Displays equal area criterion & finds critical clearing time of fault
eacpower(PO,E,V,X)	Displays equal area criterion & max.steady-state power
xdot = afpower(t,x)	One-machine system state derivative after fault
xdot = pfpower(t,x)	One-machine system state derivative during fault
swingmeu(Pm,E,V,X1,X2, X3, H, f, tc, tf)	One-machine swing curve, modified Euler
swingrk2(Pm,E,V,X1,X2, X3, H, f, tc, tf)	One-machine swing curve, MATLAB ode23
swingrk4(Pm,E,V,X1,X2, X3, H, f, tc, tf)	One-machine swing curve, MATLAB ode34
xot = afpek(t,x)	Multimachine system derivative after fault
xdot = dfpek(t,x)	Multimachine system derivative during fault
trstab	Stabiliy analysis works in synergy with load flow
[Ybus, Ybf] = ybusbf(	Multimachine system reduced Y_{bus} before fault

linedata, yload, nbus1, nbust)	
Ypf = ybusbf(Ybus nbus1, nbust, nf)	Multimachine system reduced Y_{bus} during fault
Yaf = ybusbf(linedata, yload, nbus1, nbust, nbrt)	Multimachine system reduced Y_{bus} after fault

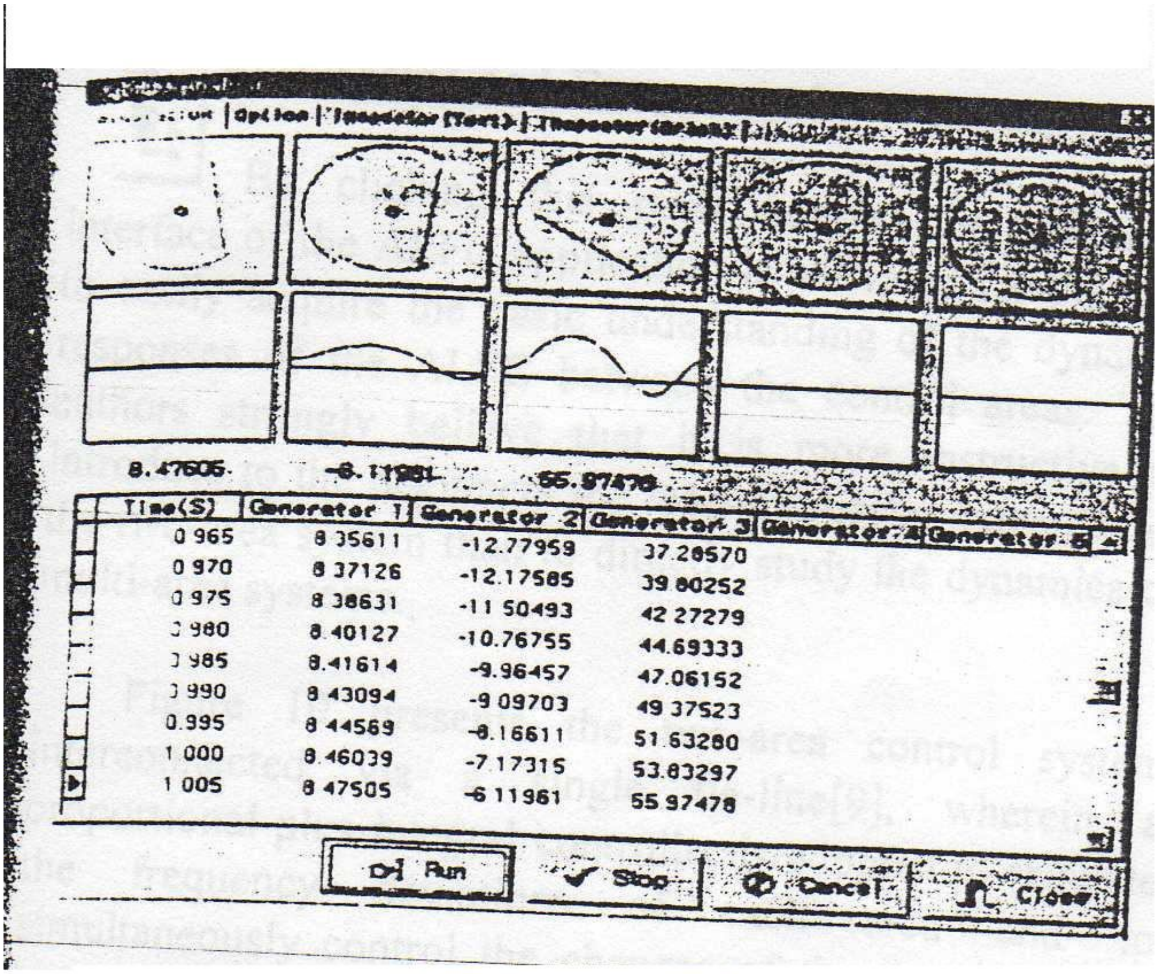
2.6 Matlab Graphical User Interface (GUI)

A graphical user interface (GUI) allows for interaction with a computer or other media formats which employ graphical images, along with text to represent the information and actions available to a user. The actions are usually performed through direct manipulation of the graphical elements which can be implemented using mouse.

A window is a rectangular portion of the monitor screen that can display its contents for example a program, icons, a text file or an image seemingly independently of the rest of the display screen [4]. A major feature is the ability for multiple windows to be open simultaneously. Each window can display a different application, or each can display different files such as text or image that have been opened or created with a single application.

An icon is a small picture or symbol in a GUI that represents a program or command, a file, a directory or a device such as a hard disk or floppy. Commands are issued in the GUI by using a mouse or touchpad to first move a pointer on the screen to, or on top of, the icon, menu item or window of interest in order to *select* that object. Then, for example, icons and windows can be moved by *dragging* which is moving the mouse with the held down and objects or programs can be opened by clicking on their icons [4].

2.7 The Similar Software In Market



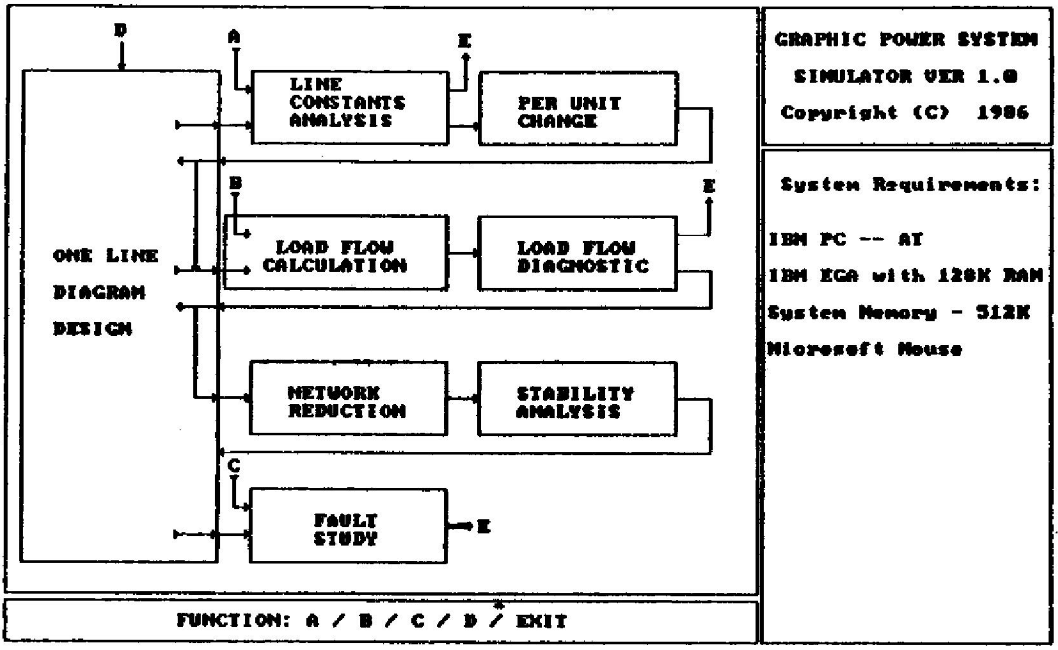
Time(S)	Generator 1	Generator 2	Generator 3	Generator 4	Generator 5
0 965	8 35611	-12.77959	37.28570		
0 970	8 37126	-12.17585	39 80252		
0 975	8 38631	-11 50493	42 27279		
0 980	8.40127	-10.76755	44.69333		
0 985	8.41614	-9.96457	47.06152		
0 990	8 43094	-9 09703	49 37523		
0.995	8 44569	-8.16611	51.63280		
1 000	8.46039	-7 17315	53.83297		
1 005	8 47505	-6 11961	55 97478		

Figure 2.5: The window for the transient stability analysis showing the animations of motion, plot, and numerical outputs of generator rotor angles.[5]

The figure above is one of the windows for the transient stability analysis of a software package named Windows-based Interactive and Graphic Package for the Education and Training of Power System Analysis and Operation. This software package is developed by Joong-Rin Shin, Wook-Hwa Lee & Dong-Hae Im from Kon-Kuk University, Seoul, Korea. This software package is developed by GUI and VDBMS using Borland C++.

The application modules developed in the package are the Power Flow (PF) calculation, the Transient Stability Analysis (TSA), the Fault Analysis (FA), the Economic Dispatch (ED), and the Automatic Load-Frequency Control (ALFC). These application software is designed as independent modules where each module has a separate graphical and interactive interfacing window and the user can easily switch from one application module to another.

The modified Euler method is used in this transient stability analysis module. In this module, the user can intuitively understand the concept of transient stability with simulation function that displays the animation of rotor motion of the involved generators [5].



GRAPHIC POWER SYSTEM
SIMULATOR VER 1.0
Copyright (C) 1986

System Requirements:
IBM PC -- AT
IBM EGA with 128K RAM
System Memory - 512K
Microsoft Mouse

Figure 2.6: The schematic diagram of graphical power system simulator .[6]

The analytical programs of the new graphical power system simulator (GSPS) consist of five subjects which are line constant analysis, system one-line diagram design, load-flow analysis, stability analysis and fault study are developed by David C.Yu, Shin-Tzo Chen and Robert F. Bischke from Milwaukee, Wisconsin.

Each subject is a module, and is properly linked as shown in Figure 2 and students can easily study a single subject or multiple subjects according to the links.

In the stability program developed by David C.Yu, Shin-Tzo Chen and Robert F. Bischke, the author developed 5 different machine models.They range from model one (constant voltage behind a transient reactance) to model five (including the effects of the field coil and a single damper in the direct axis and a set of 2 damper coils in the q axis) [6]. The program can represent five different forms of exciter systems which are a no excitation system, IEEE static excitation system, IEEE rotating excitation system with or without stabilizer, and a first order approximation excitation system.The stability analysis also has four different types of turbine governor models which are IEEE steam turbine and governor model, IEEE waterwheel turbine and governor model, a PECO generalized steam and hydro turbine governor model, and a first order steam and hydro model for turbine governor. Students use the mouse to assign the fault bus in the one- line diagram, and specified the time of the fault and the type of the fault. To correct the fault, the student then enters the type of action, and the time of action [6].

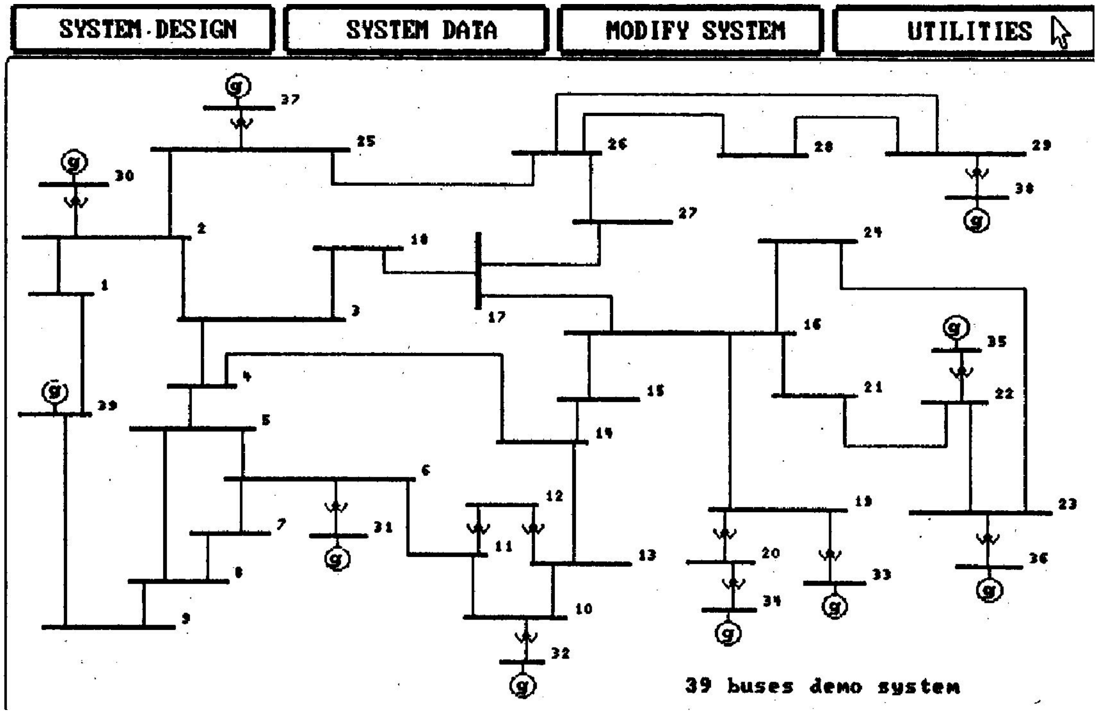
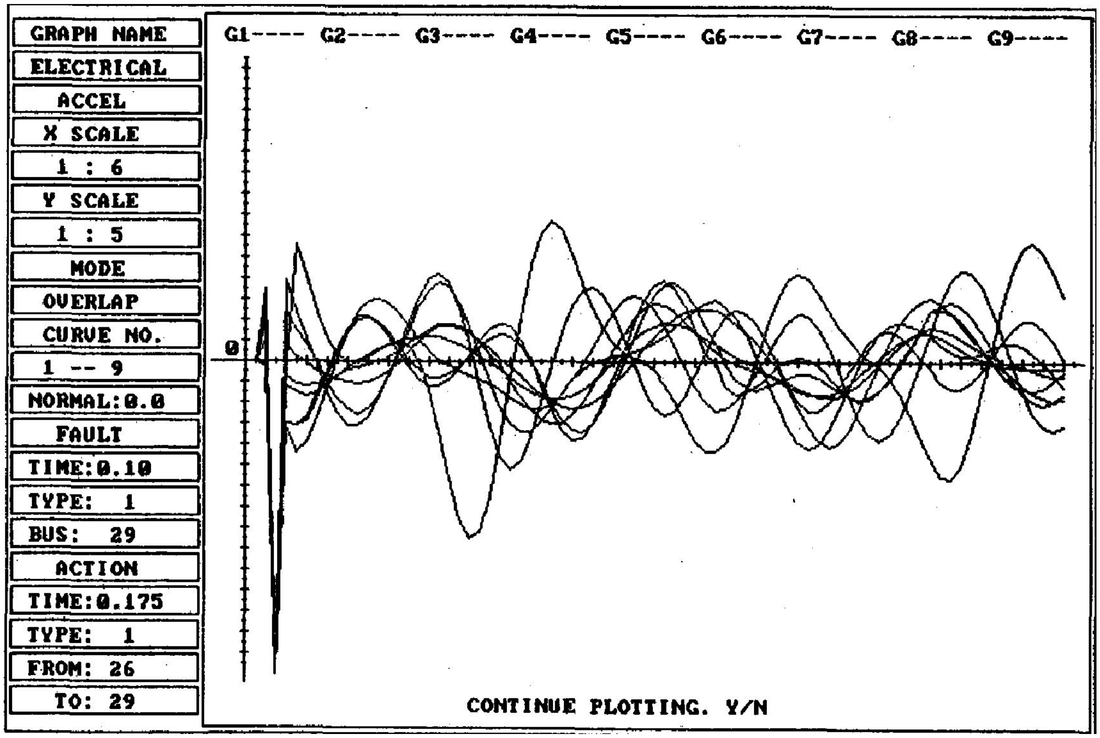


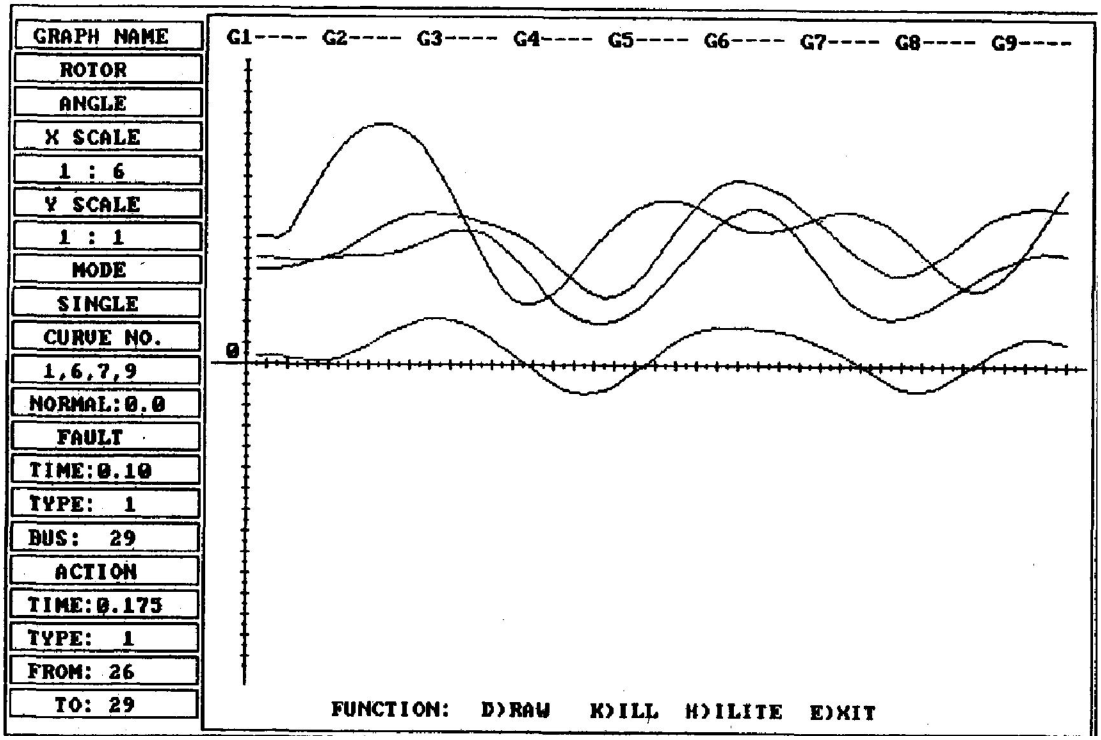
Figure 2.7: The one line diagram of IEEE 39 bus system built in this program.[6]

The example of the IEEE 39 bus system using machine model 5, IEEE rotating excitation system, and PECO turbine governor model is implemented in the stability module. A three phase fault is placed at bus 29 at 0.1 second. Following the fault, a line 26-29 is removed at the 0.175 second and the simulation lasts for 4 seconds. The integration step is 0.01 second, and the data are sampled for every 0.05 second.The result is shown in Figure 4 and Figure 5


GRAPH NAME
ELECTRICAL
ACCEL
X SCALE
1 : 6
Y SCALE
1 : 5
MODE
OVERLAP
CURVE NO.
1 -- 9
NORMAL:0.0
FAULT
TIME:0.10
TYPE: 1
BUS: 29
ACTION
TIME:0.175
TYPE: 1
FROM: 26
TO: 29

CONTINUE PLOTTING. Y/N

Figure 2.8: The curves of electrical accleration angles of generator 1-9 .[6]


GRAPH NAME
ROTOR
ANGLE
X SCALE
1 : 6
Y SCALE
1 : 1
MODE
SINGLE
CURVE NO.
1,6,7,9
NORMAL:0.0
FAULT
TIME:0.10
TYPE: 1
BUS: 29
ACTION
TIME:0.175
TYPE: 1
FROM: 26
TO: 29

FUNCTION: D)RAW K)ILL H)ILITE E)XIT

Figure 2.9: The curves of rotor angle characteristics of generators 1,6, 7, and 9. [6].

The other authors that had developed other simmilar toolbox is Karl Schoder, Amer Hasanovic´, Ali Feliachi and Azra Hasanovic. The transient module targets the balanced-power system transient studies and is organized as a Simulink-Block library and allows the user to build a case file via a drag-and-drop feature which are provided by Simulink. Each block in the PAT library models one type of device such as subtransient machine model and UPFC model. Each block is vectorized, meaning that the user needs to add only one block to the Simulink MDL-case file to represent a number of devices of the same type. For example, if there are detailed machines and classical machines (EM) in a case study one subtransient block and one EM-block will be used from the PAT library to perform the simulation. The internals of each block have been modeled by Simulink built-in blocks and/or MATLAB-S functions. Using the utilization of Simulink's ability to propagate complex vectors as signals between blocks achieved a great improvement in simulation speed [7].

Ali Abur, Fernando Magnago andYunqiang Lu had also developed an educational toolbox for Power System Analysis. When the transient-analysis mode is chosen, the user can select among the options available for setting the simulation time, time step, fault location, fault initiation and clearing times, and convergence tolerance [8]. Simulations are carried out using a user-specified, fixed time step in this initial implementation.

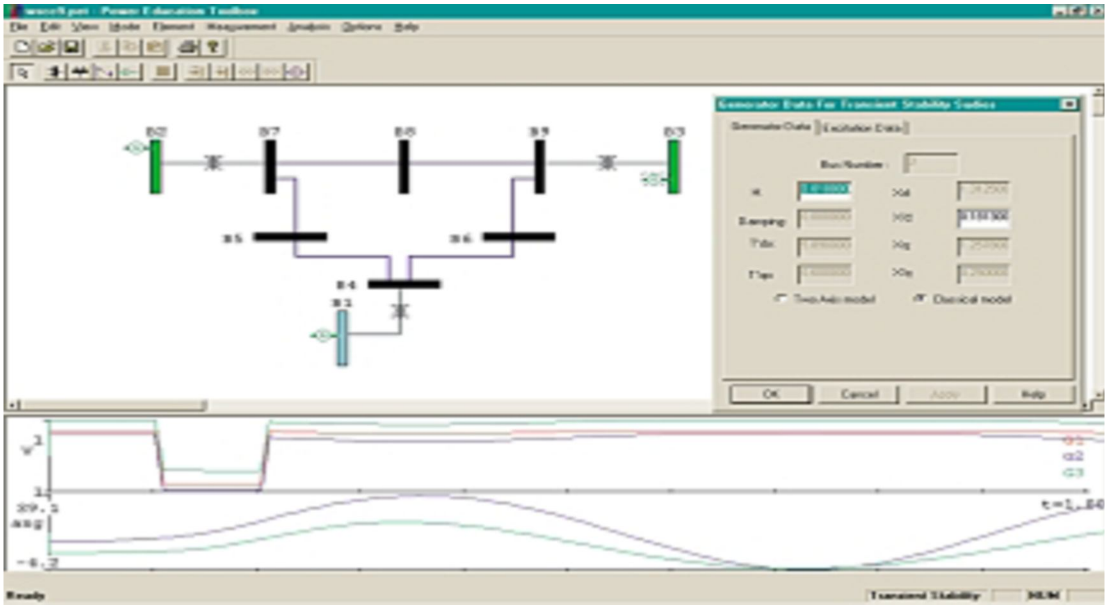


Figure 2.10: Simulation data entry in the Transient stability analysis mode .[8]

In this example shown in Figure 6, the dialog box used for entering parameters of the generators and exciters as well as the options menu for specifying the output variables.For this example, a three-phase fault at bus 5 occurs at 0.1 s and is cleared at 0.2 s. The relative rotor angles of generators with respect to the reference bus 1 are plotted in the lower window.[8]

CHAPTER 3

METHODOLOGY

This chapter explains the development process of a toolbox for steady state and transient stability analysis with MATLAB.

3.1 Background

In this chapter there are four major stages that the development of steady state and transient will go through which are planning,requirement and analysis, toolbox design and develoment as well as the toolbox implementation and testing. Every stage plays its own role throughout the develoment process of steady state and transient stability analysis toolbox.

The first stage is planning which describe the project planning using Gantt Chart. The second stage is the analysis and requirement of the toolbox of steady state and transient stability analysis with MATLAB. This stage will describe the requirement of the steady state and transient analysis toolbox with MATLAB.

The third stage is toolbox design where all the design of the toolbox will be defined in this stage. Finally, the last stage is toolbox implementation and testing. The coding implementation will be defined in this stage as well as the testing process.

3.2 Flow Chart Of Project

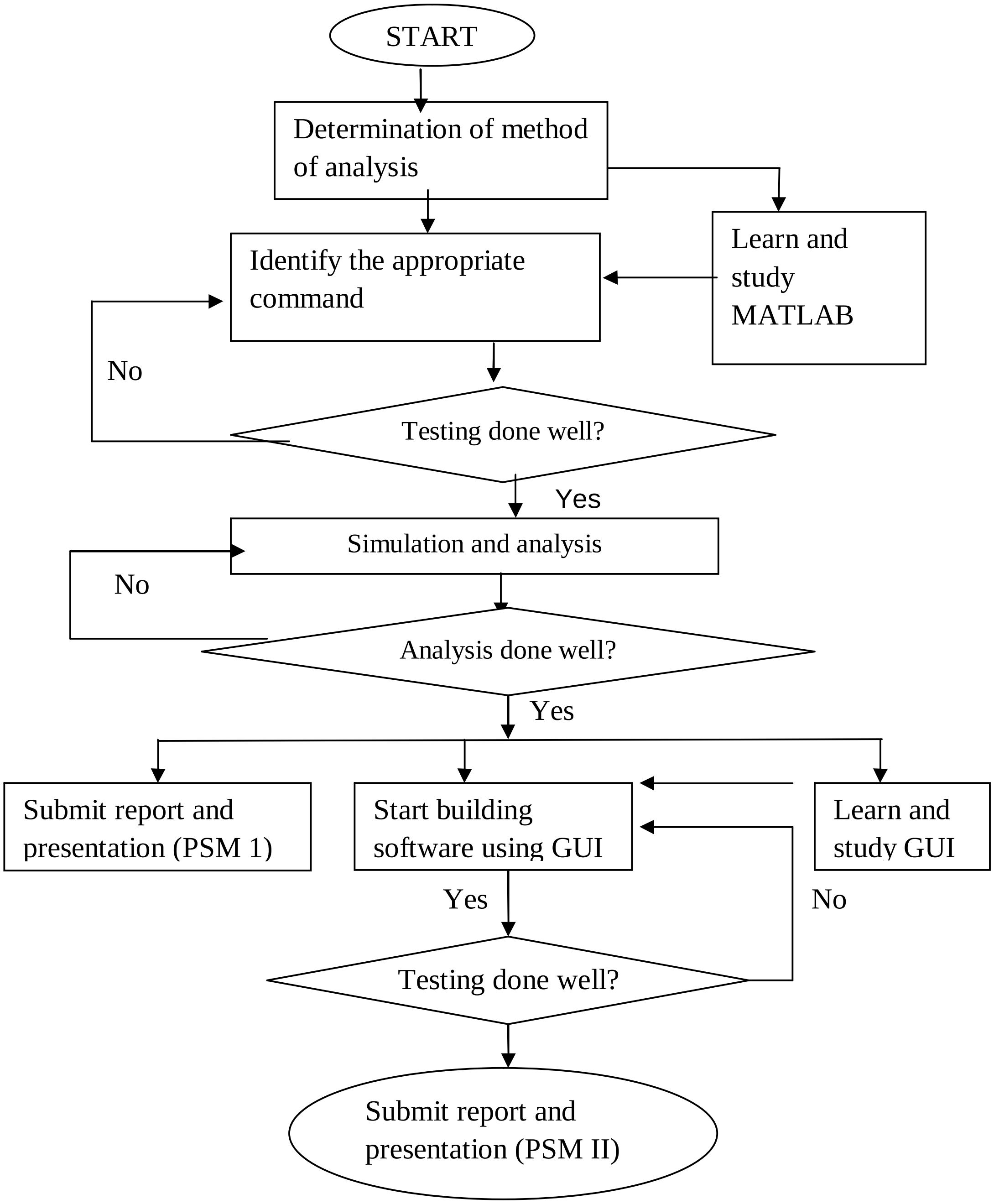


Figure 3.1: The flowchart of the project

3.3 Planning

The planning phase is the first stage in developing of the toolbox for steady state and transient stability analysis with MATLAB. The planning in this toolbox development begins by defining the problem statement, scopes and the objectives. In the beginning of this project development, the problem statement is the first thing to define where the manual calculation using calculator and formula and also the simulation of the steady state stability and transient stability maybe take a long time for student to understand the theory part of stability. The existance of transient and steady state toolbox will help us to create faster transient and steady state analysis.Then, the problem statement will define the objectives of the project.

3.4 Information Acquisition

The information of this project is taken from two types of resources which are books and internet in order to get the information for this project. The Power System Analysis written by Hadi Saadat will give information about steady state and transient stability. Other power system related books are also needed to give more information about steady state and transient stability. The internet resources give lots of information about the development of the simillar toolbox developed by other people in other country. This resource give many details of the toolbox developed by other people in other country. The combination of the two resources makes it easy to define the requirement for this project.

3.5 Software Requirement

In this part, it describes the software requirement that the toolbox needed during the development process until implementation and testing. This software is very important to the development of this transient stability analysis toolbox in order to provide a suitable environment for the toolbox to run any testing during the implementation process. The software used in developing toolbox of steady state and transient stability analysis is MATLAB 7.0

3.6 Functional Requirement

The functional requirement is what the toolbox should perform or do. For this toolbox it has five functional requirements which are equal area criterion, application to sudden increase in power input, application to three phase fault, numerical solution of nonlinear equation, numerical solution of swing equation and multimachine transient stability. These functional requirements are very important and the toolbox should be able to perform the function of these requirements. The functional requirements will produce the result based on the users input.

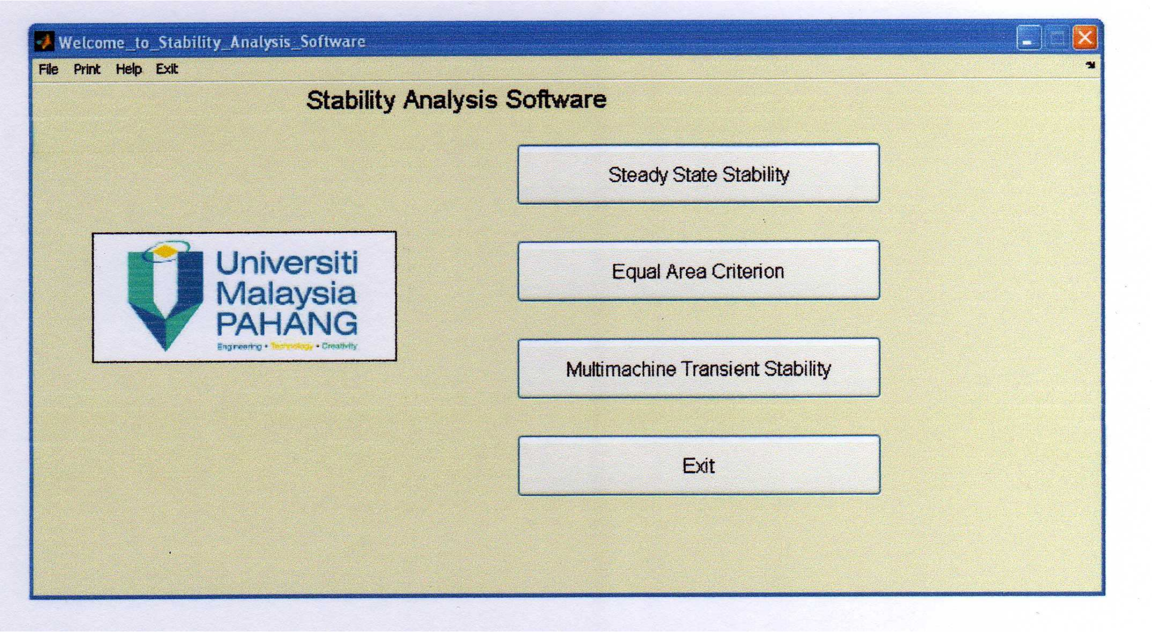


Figure 3.2: The functional requirements of stability analysis toolbox in MATLAB

3.6.1 Interface Simplicity

For this toolbox, it is using a simple graphical user interface (GUI) so that the user could use it in a simple way. The user can directly view the toolbox as they browse the toolbox. It would be easy for the user to understand how to use the stability analysis toolbox as it is designed for simple user interface.

3.6.2 Result Accuracy

The result of the transient analysis on the toolbox depends on how accurate the equation defined in the MATLAB and the algorithm and source code used in the programming of MATLAB and this result will be verified with manual calculation to confirm the toolbox produce the correct and accurate result.

3.6.3 Time Consumption

Time is an issue that should be given attention by the designer of any toolbox. For this toolbox, it just takes a few minutes to finish all the transient stability analysis simulation and calculation and the user can get the result instantly.

3.7 Software Design

In this part, it will describe the graphical user interface design and programming of the database. The graphical user interface defines the front page of the application of this system where the user can interact with the toolbox through the graphical user interface.

The database will store all the data needed by the toolbox in order to produce the required result to the users.Any input entered by the users using the graphical user interface will be processed using the database and the result produced will be send back to the interface.

3.7.1 Graphical User Interface Design

The graphical user interface of this toolbox is designed to be simple to avoid the complexity that may confuse or causing trouble to the users while using the toolbox. The toolbox consists of two graphical user interfaces which are the main page and the result page. The selection of the tasks are placed on the main page of the toolbox.The tasks in this stability analysis toolbox would be steady state stability, equal area criterion which consists of application to sudden increase in power input and application to three phase fault and multimachine transient stability. The result page which consist of the calculated parameters and the simulation will appear right after all input parameters are processed.The simplicity of this graphical user interface is shown here where usere need only to key in the input parameters and then click the push button to get the desired result and this will make it easy for user to use and understand. This graphical user interface is build using Graphical User Interface Development Environment (GUIDE). The main page and the example of the simulation are shown in Figure 3.2, 3.3 and 3.4

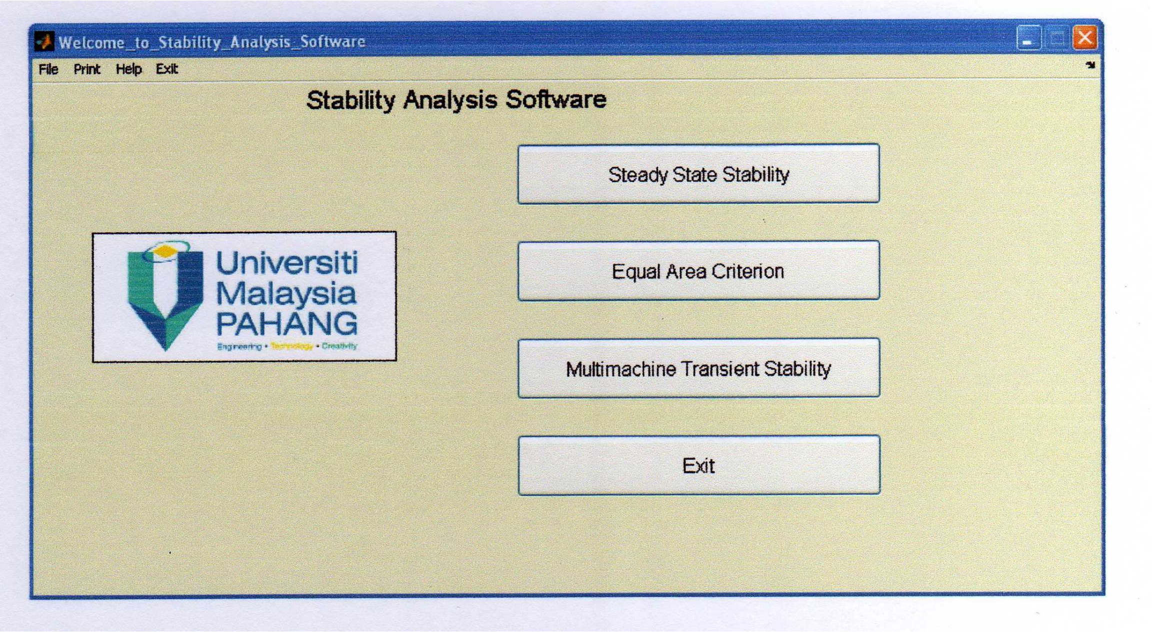


Figure 3.3: The main page of the stability toolbox

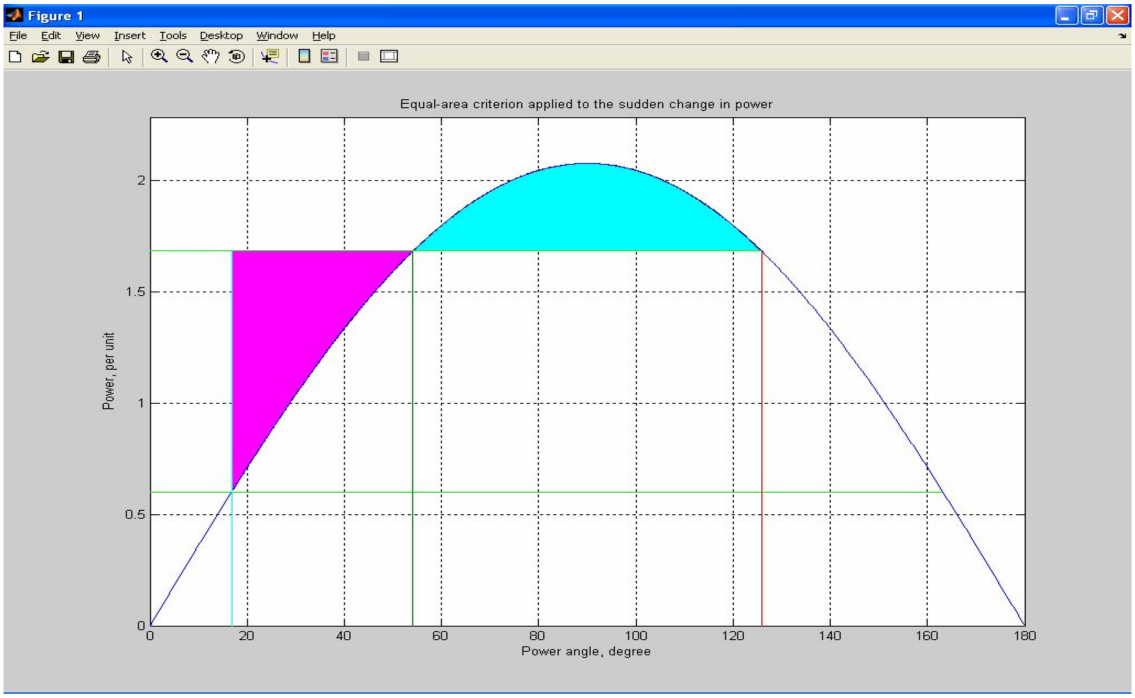
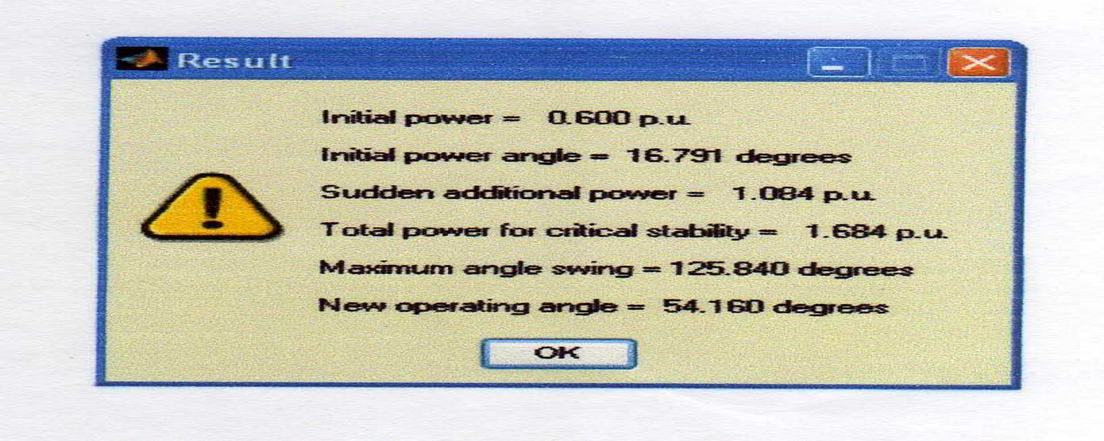


Figure 3.4: One of the examples of the result page which shows the result for the Equal Area Criterion Simulation due to sudden change in power



```
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
```

Figure 3.5: One of the examples of the result page which shows the result of the important parameters needed for stability analysis

3.7.2 Database Design

The database programming is done using a branching command which is the command **if**.This command is needed when we wants a function to perform a different sequence of commands in different cases depending on the input.

In general, **if** must be followed on the same line by an expression that MATLAB will test to be true or false. After some commands, there must be an **end** statement. In between, there may be one or more **elseif** statements or an **else** statement, If the result of the test is true, MATLAB executes all commands between the **if** statement and the first **elseif**, **else** or **end** statement, then skips all commands between the if statement and the first **elseif**,**else** or **end** statement,then skips all commands until after the **end** statement and proceeds from there, carrying out a new test in the case of an **elseif** statement.

The author also uses relational operations such as >=, > and = = to form a logical expression and instructed MATLAB to choose between different commands according to whether the expression is true or false.

The author also use the command **eval** which allow to run a command that is stored in a string as if the author had typed the string on the command line. **eval** us used in an M-File to define a variable or run a command whose name depends on an input or loop variable.The command **eval** is also used when there is two input strings where it will try the first command and if there is an error,it will try the second command.

In order to print a message to the screen without stoping the execution on an M-File, the author use the command **disp** or **warning.**

During the development of the toolbox, the MATLAB also provide help when there is error in programming by using the debugging tools provided by MATLAB.This debugging tool will show which line has the error and the author will solve the error by correcting and typing a new program.

CHAPTER 4

RESULT AND DISCUSSION

This chapter will provide the result of the simulation,the user guide on how to use the stability analysis toolbox and discussions about the simulation.

4.1 User Guide On How To Use The Stability Analysis Toolbox

The Stability Analysis Toolbox is given into three sections which are the steady state stability, equal area criterion and multimachine transient stability. The flow chart of the stability analysis toolbox is shown in the Figure 4.1 in the next page.

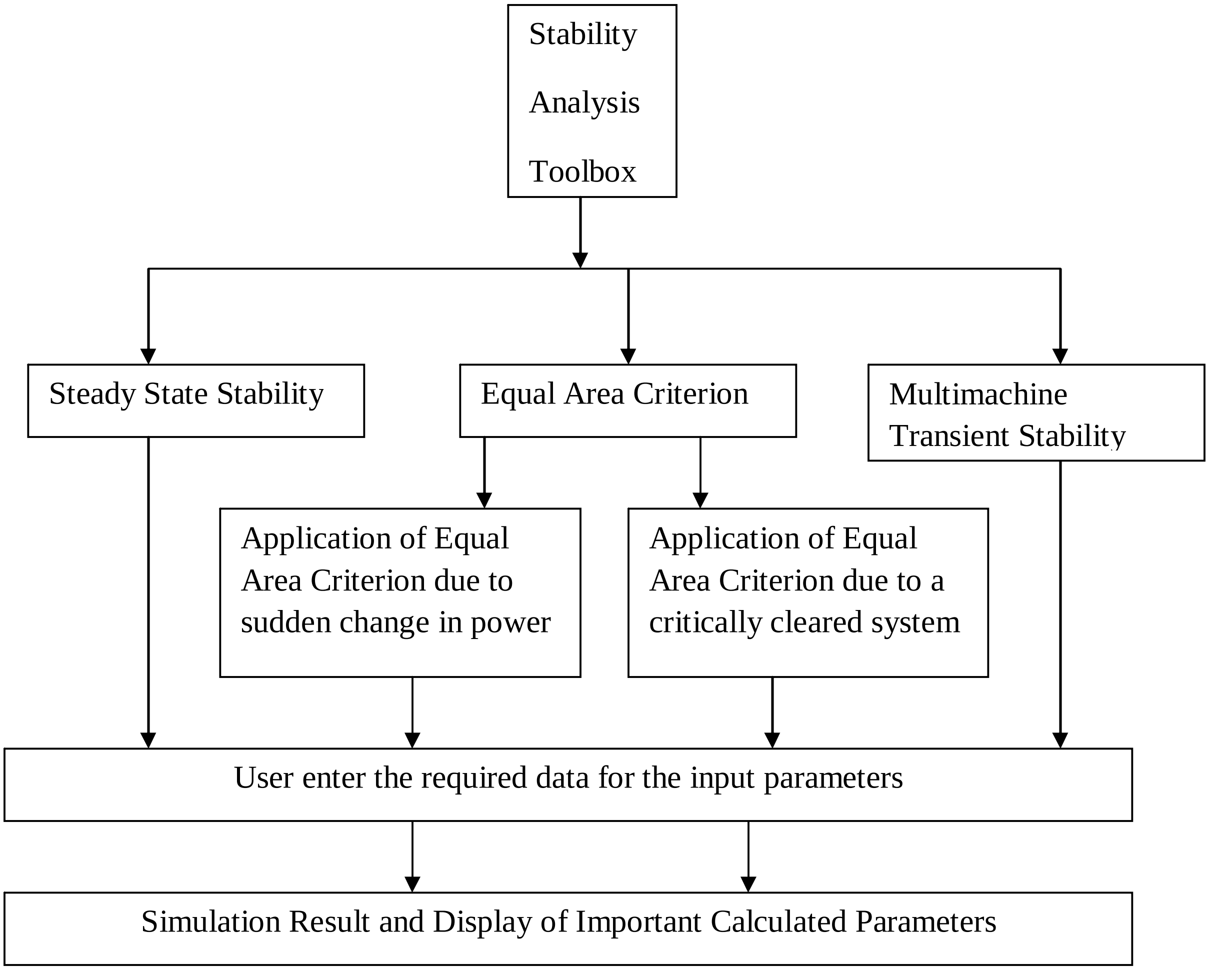


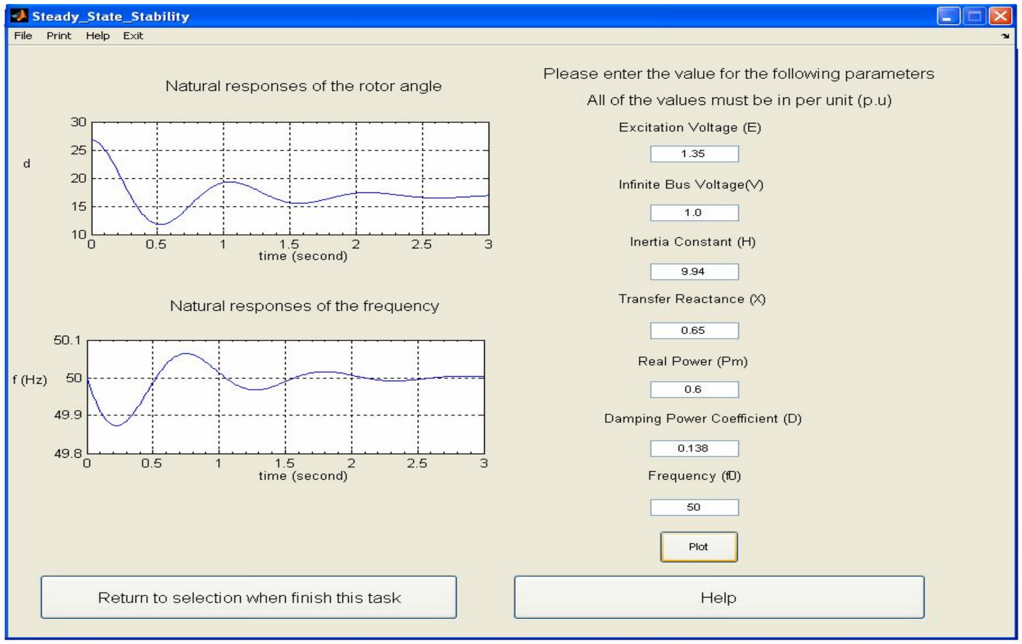
Figure 4.1: Flow chart that shows the flow of the stability analysis toolbox.

Based on the figure above, when the user click the push button that has the required application, the user will need to enter data to obtain the simulation and the result of the calculated parameters.Therefore, the next section will show the users how to use the stability toolbox step by step.

4.1.1 User Guide On How To Use Steady State Stability Application In Stability Analysis Toolbox

First, the user need to click the pushbutton that display steady state criteria.Then, the page that display the required parameters will be shown. User need to enter the value for the parameters of Excitation Voltage(E), Infinite Bus Voltage (V), Inertia Constant (H), Transfer Reactance (X), Real Power (Pm), Damping Power Coefficient(D), Frequency (f0).

After the parameters is entered, then user will only to click the plot button and the simulation of natural responses of the rotor angle and simulation of natural responses of the frequency will be shown.If user need help during doing this task, user can always click the help button.When the user finish doing this steady state criteria, then the user can either return to main page by clicking the button that displays the “return to selection when finish the task” or simply exit the whole stability analysis toolbox.



Please enter the value for the following parameters

All of the values must be in per unit (p.u)

Excitation Voltage (E)
1.35

Infinite Bus Voltage(V)
1.0

Inertia Constant (H)
9.94

Transfer Reactance (X)
0.65

Real Power (Pm)
0.6

Damping Power Coefficient (D)
0.138

Frequency (f0)
50

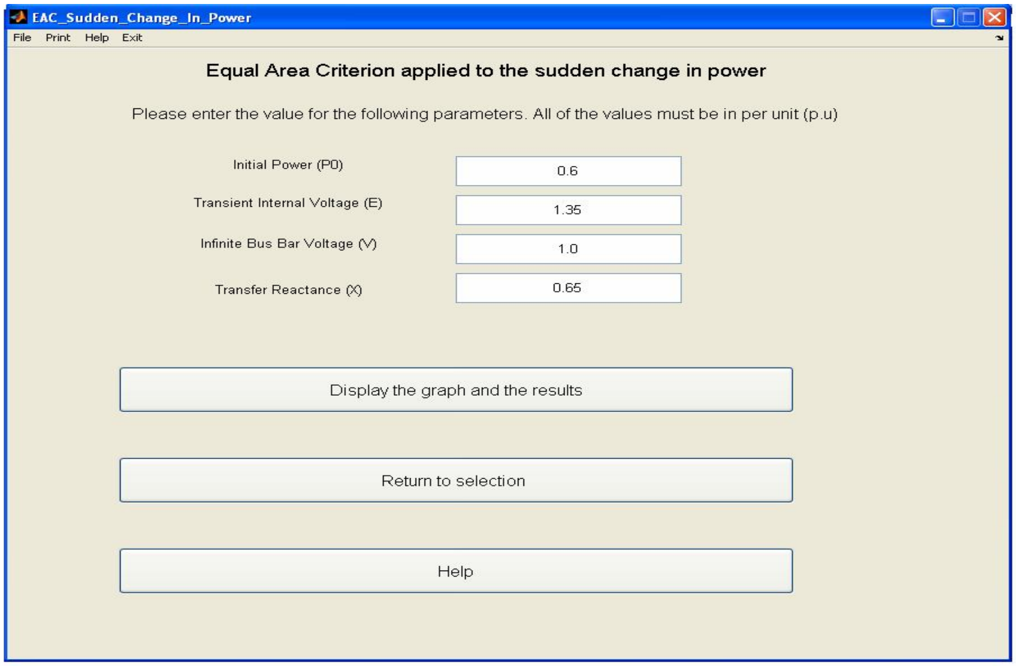
Figure 4.2: The page that displays the input parameters and simulation result of steady state stability

4.1.2 User Guide On How To Use Equal Area Application In Stability Analysis Toolbox

First, the user need to click the pushbutton that display equal area criterion.Then, the page that display type of equal area criterion will be shown. The user need to choose between the application of equal area criterion due to sudden change in power or the application of equal area criterion due to a critically cleared system.

Next, if the user choose the application of equal area criterion due to sudden change in power, then the user need to enter the value for the parameters of Initial Power (P0), Transient Internal Voltage(E), Infinite Bus Bar Voltage (V), and Transfer Reactance (X),

After the parameters is entered, then user will only to click the display the graph and results button and the simulation of equal area criterion due to sudden change in power and the results calculated will be shown on the screen.If user need help during doing this task, user can always click the help button.When the user finish doing this equal area criterion due to sudden change in power, then the user can either return to main page by clicking the button that displays the “return to selection ” or simply exit the whole stability analysis toolbox.



Equal Area Criterion applied to the sudden change in power

Please enter the value for the following parameters. All of the values must be in per unit (p.u)

Initial Power (P0): 0.6
Transient Internal Voltage (E): 1.35
Infinite Bus Bar Voltage (V): 1.0
Transfer Reactance (X): 0.65

Figure 4.3: The page that displays the input parameters needed to display the simulation of equal area criterion applied to sudden change in power

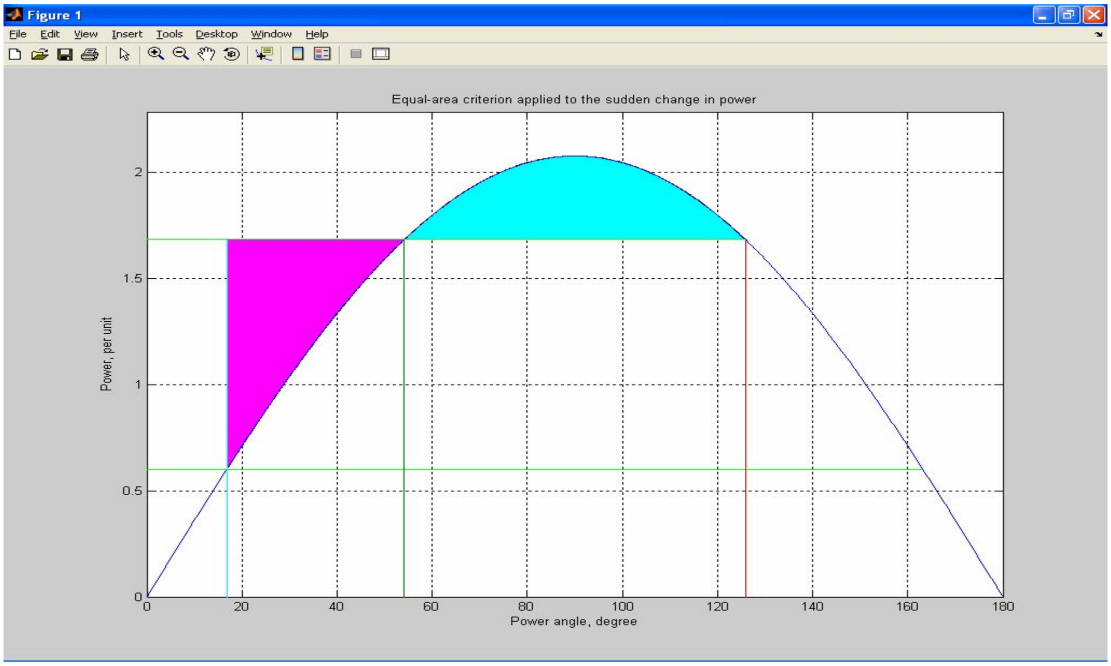
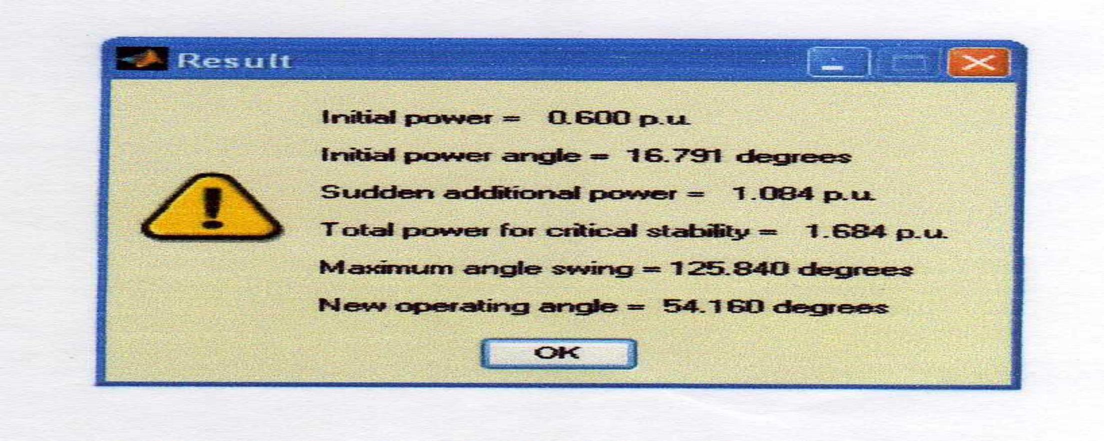


Figure 4.4: The simulation of equal area criterion applied to sudden change in power after the user entered the important parameters.



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

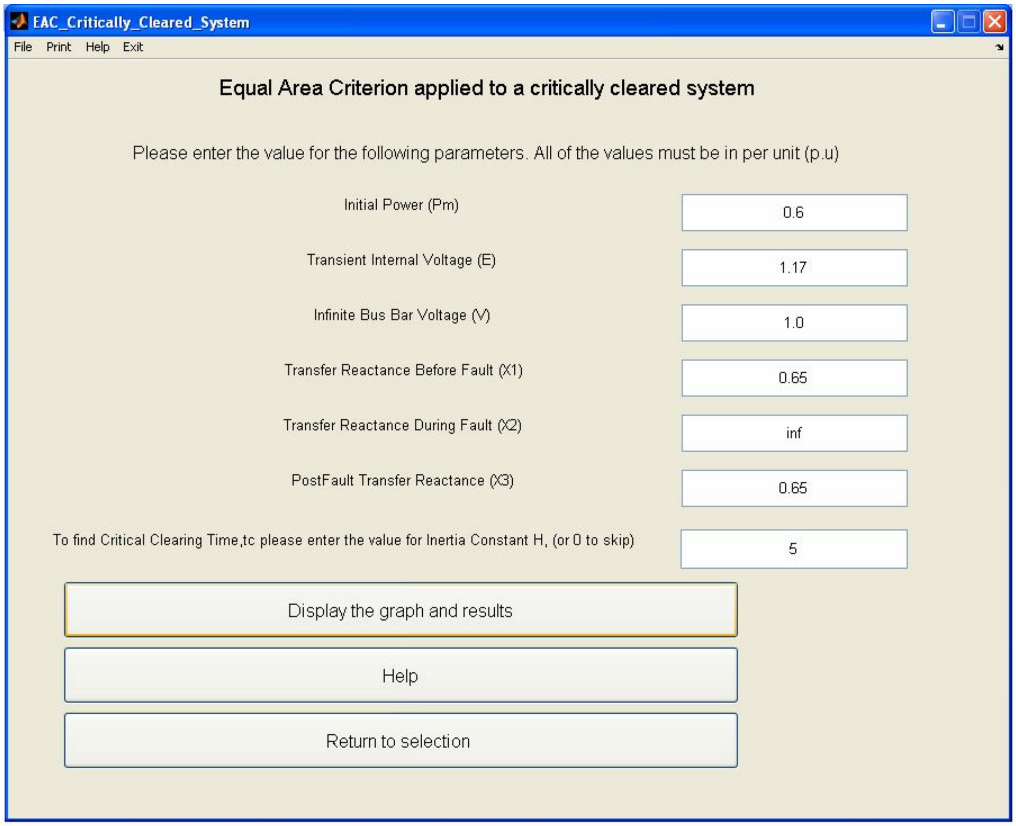
Figure 4.5: The calculated results that related to equal area criterion applied to sudden change in power after the user entered the important parameters.

If the user click the the application of equal area criterion due to a critically cleared system, then the user need to enter the value for the parameters of Initial Power (Pm), Transient Internal Voltage(E), Infinite Bus Bar Voltage (V), Transfer Reactance Before Fault (X1), Transfer Reactance During Fault (X2) and Post Fault Transfer Reactance (X3).Extra care must be taken when entering the value for Transfer Reactance During Fault (X2) where when 3 phase fault occurs at the sending end of the line, the value that need to be entered is **inf**. When the 3 phase fault occurs at the middle of the line,then the value of Transfer Reactance During Fault (X2) is according to the situation.

The user is also given an option whether to allow the toolbox to calculate the critical clearing time (tc) .This can be done by entering the inertia constant (H) or if the user do not want to find the critical clearing time (tc), the user can enter the value 0 to skip.

After the parameters is entered, then user will only to click the display the graph and results button and the simulation of equal area criterion due to to a critically cleared system,and the results calculated will be shown on the screen.If user need help during doing this task, user can always click the help button.

When the user finish doing this equal area criterion due to to a critically cleared system, then the user can either return to main page by clicking the button that displays the “return to selection ” or simply exit the whole stability analysis toolbox.



Equal Area Criterion applied to a critically cleared system

Please enter the value for the following parameters. All of the values must be in per unit (p.u)

Initial Power (Pm) 0.6
Transient Internal Voltage (E) 1.17
Infinite Bus Bar Voltage (V) 1.0
Transfer Reactance Before Fault (X1) 0.65
Transfer Reactance During Fault (X2) inf
PostFault Transfer Reactance (X3) 0.65
To find Critical Clearing Time,tc please enter the value for Inertia Constant H, (or 0 to skip) 5

Figure 4.6: The page that displays the input parameters needed to display the simulation of equal area criterion applied to a critically cleared system due to 3 phase fault occurs at the sending end of the line

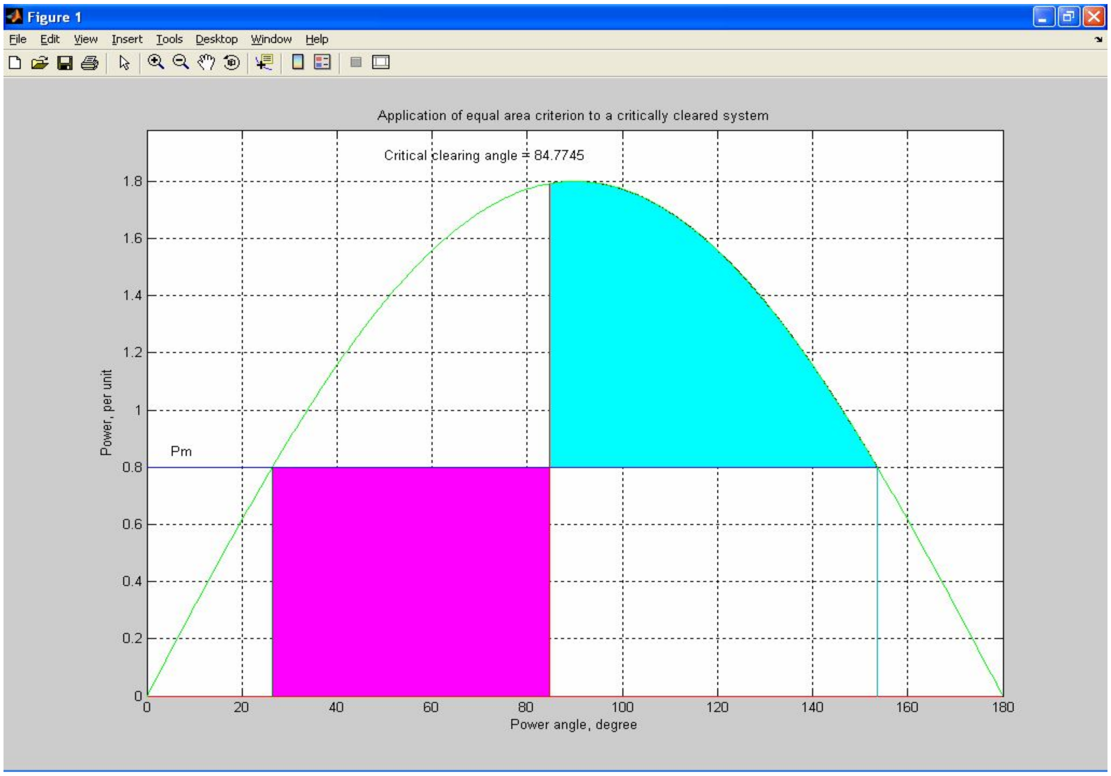
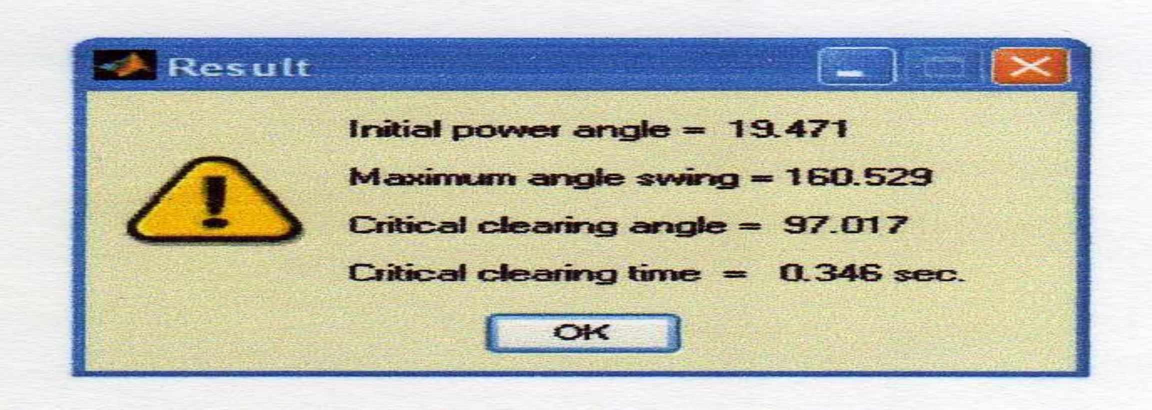


Figure 4.7: The simulation of equal area criterion applied to critically cleared system due to 3 phase fault occurs at the sending end of the line after the user entered the important parameters.



Initial power angle = 19.471

Maximum angle swing = 160.529

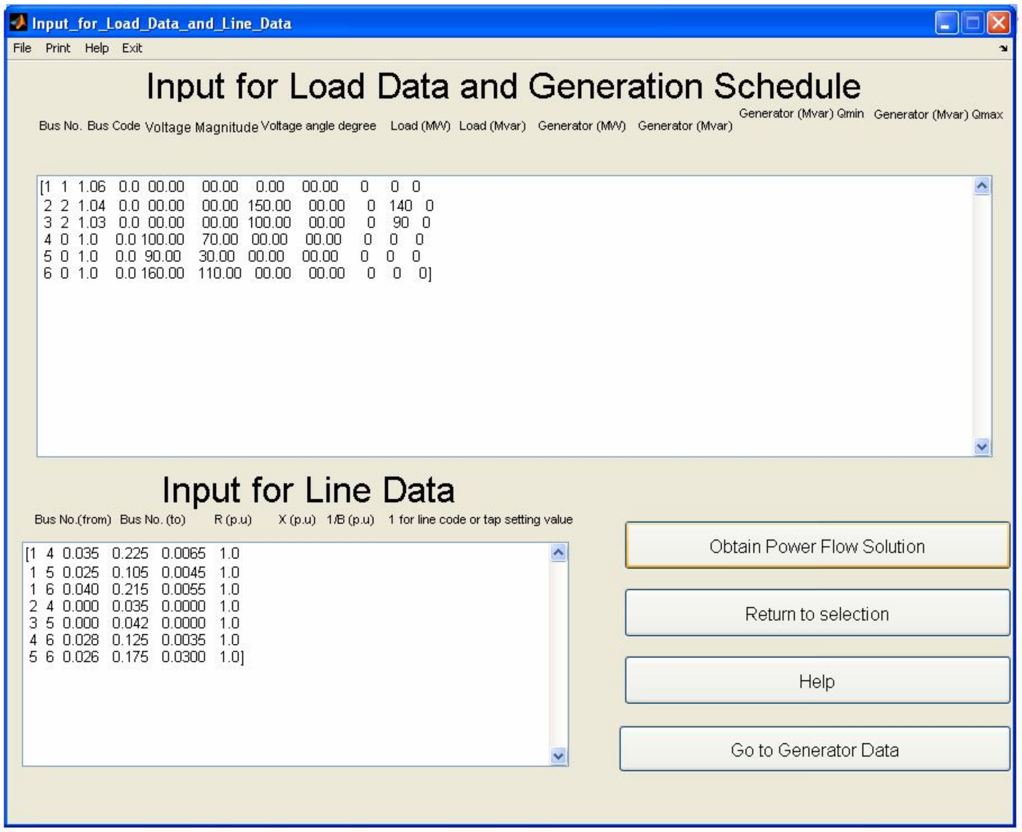
Critical clearing angle = 97.017

Critical clearing time = 0.346 sec.

Figure 4.8: The calculated results that related to equal area criterion applied to critically cleared system where fault occurs at the sending end of the line after the user entered the important parameters.

4.1.3 User Guide On How To Use Multimachine Transient Stability In Stability Analysis Toolbox

First, the user need to click the pushbutton that display multimachine transient stability..Then, the page that required user to enter the input for load data and line data will be shown. User will enter the input for load data and line data based on the situations.

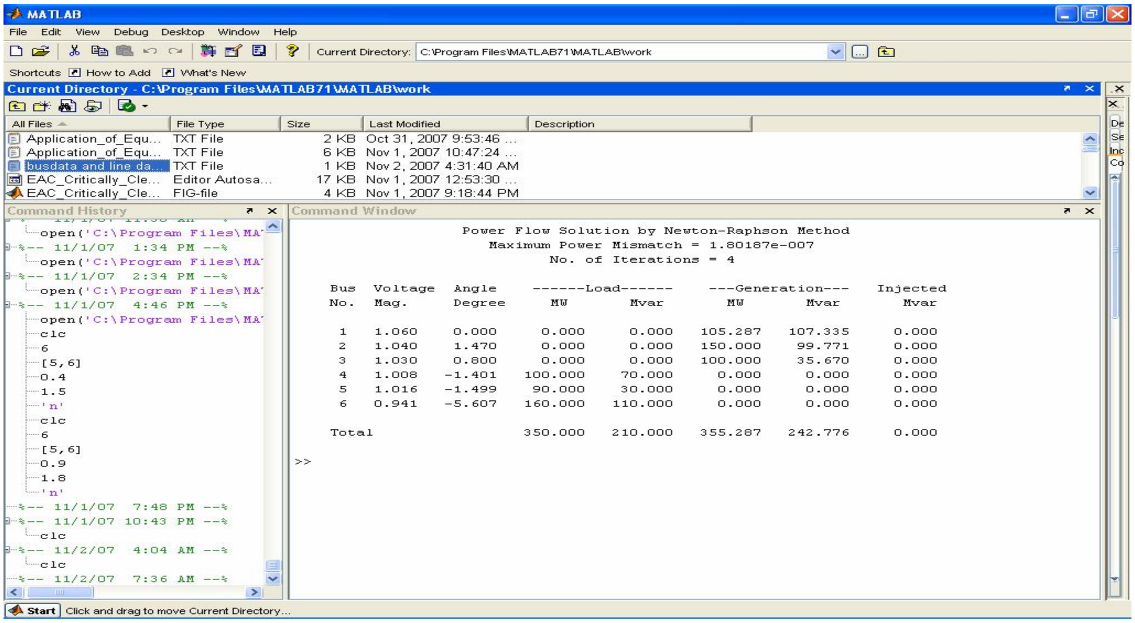


```
[1  1  1.06   0.0  00.00    00.00    0.00    00.00     0     0   0
 2  2  1.04   0.0  00.00    00.00  150.00    00.00     0   140   0
 3  2  1.03   0.0  00.00    00.00  100.00    00.00     0    90   0
 4  0  1.0    0.0 100.00    70.00   00.00    00.00     0     0   0
 5  0  1.0    0.0  90.00    30.00   00.00    00.00     0     0   0
 6  0  1.0    0.0 160.00   110.00   00.00    00.00     0     0   0]
```

```
[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]
```

Figure 4.9: The page that displays the input parameters for load data and line data needed to display the power flow solution.

Then , power flow solution would be displayed at MATLAB Command Window



All Files	File Type	Size	Last Modified	Description
Application_of_Equ...	TXT File	2 KB	Oct 31, 2007 9:53:46 ...	
Application_of_Equ...	TXT File	6 KB	Nov 1, 2007 10:47:24 ...	
busdata and line da...	TXT File	1 KB	Nov 2, 2007 4:31:40 AM	
EAC_Critically_Cle...	Editor Autosa...	17 KB	Nov 1, 2007 12:53:30 ...	
EAC_Critically_Cle...	FIG-file	4 KB	Nov 1, 2007 9:18:44 PM	

```
   open('C:\Program Files\MA
%-- 11/1/07  1:34 PM --%
   open('C:\Program Files\MA
%-- 11/1/07  2:34 PM --%
   open('C:\Program Files\MA
%-- 11/1/07  4:46 PM --%
   open('C:\Program Files\MA
   clc
   6
   [5,6]
   0.4
   1.5
   'n'
   clc
   6
   [5,6]
   0.9
   1.8
   'n'
%-- 11/1/07  7:48 PM --%
%-- 11/1/07 10:43 PM --%
   clc
%-- 11/2/07  4:04 AM --%
   clc
%-- 11/2/07  7:36 AM --%
```

```
                  Power Flow Solution by Newton-Raphson Method
                     Maximum Power Mismatch = 1.80187e-007
                            No. of Iterations = 4

 Bus  Voltage  Angle     ------Load------     ---Generation---    Injected
 No.  Mag.     Degree     MW        Mvar        MW        Mvar      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

>>
```

Figure 4.10: Power Flow Solution on Command Window

Power flow solution will be combined with generator data to obtain the prefault bus admittance matrix, reduced faulted bus admittance matrix and reduced postfault bus admittance matrix. However, the stability analysis toolbox that is developed by this author would only obtain the power flow solution and cannot obtain the multimachine transient stability.

4.2 Analysis Of Steady State And Transient Stability Simulation

In this part, the result of steady state and transient stability simulation is obtained using the MATLAB power system toolbox.

4.2.1 Result For Steady State Stability-Small Disturbances Using Initial Function

For this case of steady state stability which is caused by small disturbances due to small power impacts, the synchronous generator has a frequency of 60 Hz , the inertia constant,H= 9.94 MJ/MVA and a transient reactance of X'd = 0.3 per unit and this synchronous generator is connected to an infinite bus through a purely reactive circuit.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.The one line diagram is shown as in the Figure 4.12

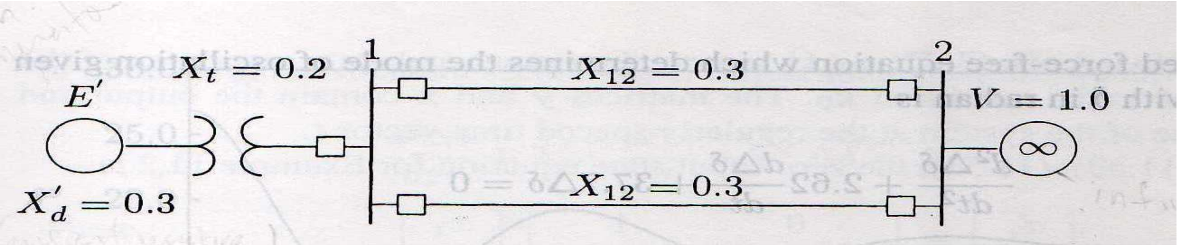


Figure 4.11: The one line diagram for the case study of steady state stability caused by small distubances due to small power impacts. [1]

In this case, we assumed that the per unit damping power coefficient, D is 0.138 and the small disturbance value is 10°.Therefore, the result of the simulation is as shown as in the Figure 4.12

For the simulation on 4.2.1.which shows the result for steady state stability-small disturbances using initial function.The important input for this simulation is excitation volatge,E =1.35 per unit, infinite bus volatge,V = 1 per unit, inertia constant,H =9.94 MJ/MVA,transfer reactance of 0.65 per unit, real power of 0.6 per unit ,damping power coefficient,D = 0.138 and the frequency of 60 Hz.

The excitation voltage, E and transfer reactance, X value must be obtained using formula calculation and circuit analysis knowledge before we begin the simulation. The simulation shows that a small disturbance will be followed by a relatively slowly damped oscillation or known as swing, of the rotor before steady state operation at synchronous speed is resume. In this simulation, the response settles in about $t_s \simeq 4T = 4(1/1.3) \simeq 3.1$ seconds.The frequency used is 60 Hz based on the frequency in the United States.However, the 50 HZ frequency used in Malaysia can also be used to simulate the required results.

It can be simulated also that as the inertia constant H increases, the natural frequency and the damping ratio decreases, which results a longer settling time, t_s . An increase in synchronising power coefficient, Ps which can be done by incresing the value of excitation voltage, E and infinite bus voltage. V in P max where P max =(EV)/X will also results in an increase in the natural frequency and decrease in damping ratio.

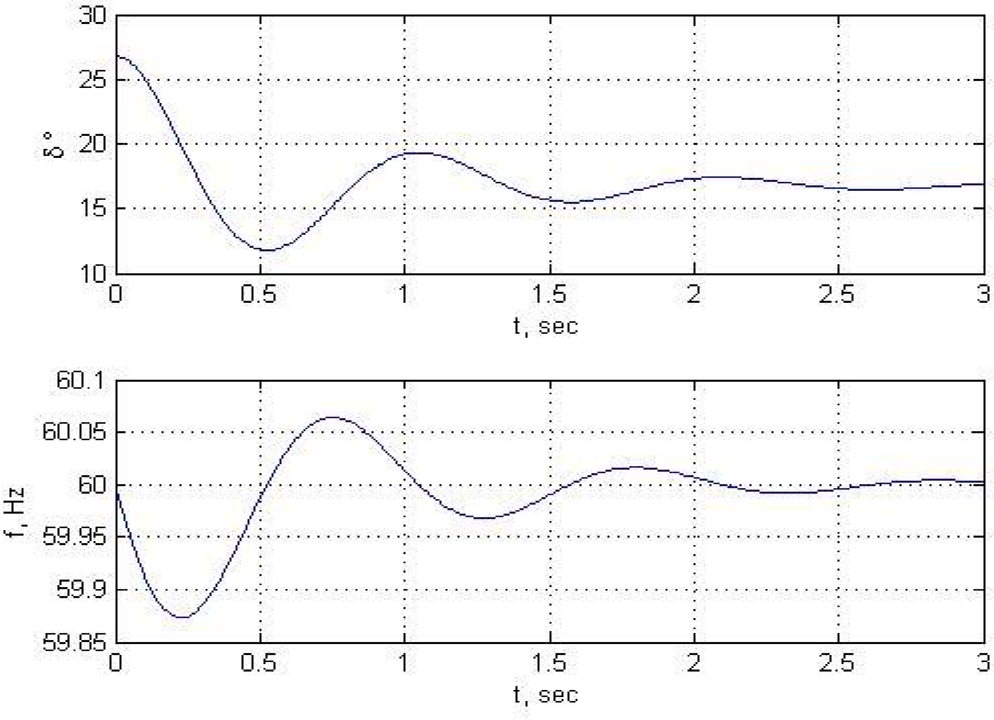


Figure 4.12: Natural responses of the rotor angle and frequency machine for steady state small disturbance simulation using initial function.

4.2.2: Result For Transient Stability Using Equal Area Criterion Due To Sudden Increase In Power Input

The simulation of result for transient stability using equal area criterion due to sudden increase in power input is done using the same example of the steady state stability caused by small disturbances due to small power impacts

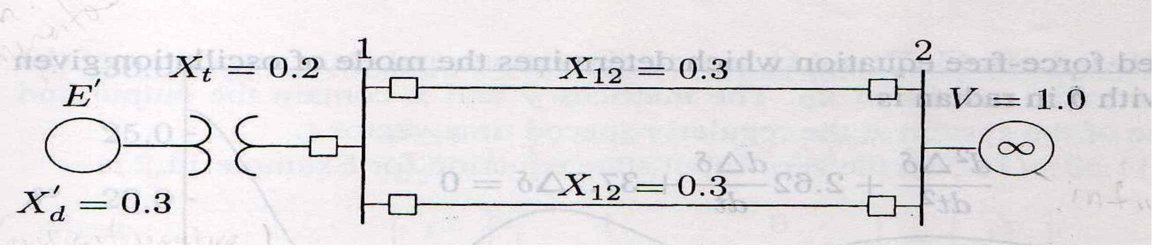


Figure 4.13: The one line diagram for the case study of transient stability using equal area criterion due to sudden increase in power input.[1]

The parameters for this example is the real power is 0.6 per unit, the power factor lagging to the infinite bus bar is at 0.8.and the infinite bus bar voltage is 1.0 per unit

From the calculation in previous example of steady state stability caused by small disturbances due to small power impacts, we can found out that the transfer reactance ,X is 0.65 per unit and the generator internal voltage, E' is 1.35 per unit

Therefore, in this simulation we will be doing two types of simulation which is to determine the maximum power input that can be applied without loss of synchronism where the initial power is stated as 0.6 per unit

The parameters needed to obtain the simulation is shown in Table 4.1 below;

Table 4.1: The important parameters for the simulation of transient stability using equal area criterion due to sudden increase in power input

Important parameters	Value (in per unit)
Initial Power (PO)	0.6
Generator internal voltage (E)	1.35
Infinite bus bar voltage (V)	1.0
Transfer Reactance (X)	0.65

The result of the simulation is shown in Table 4.2 below;

Table 4.2: The result the simulation of transient stability using equal area criterion due to sudden increase in power input.where the initial power input is 0.6 per unit

Parameters	Value
Initial power	0.600 per.unit
Initial power angle	16.791 degrees
Sudden additional power	1.084 per.unit
Total power for critical stability	1.684 per.unit
Maximum angle swing	125.840 degrees
New operating angle	54.160 degrees

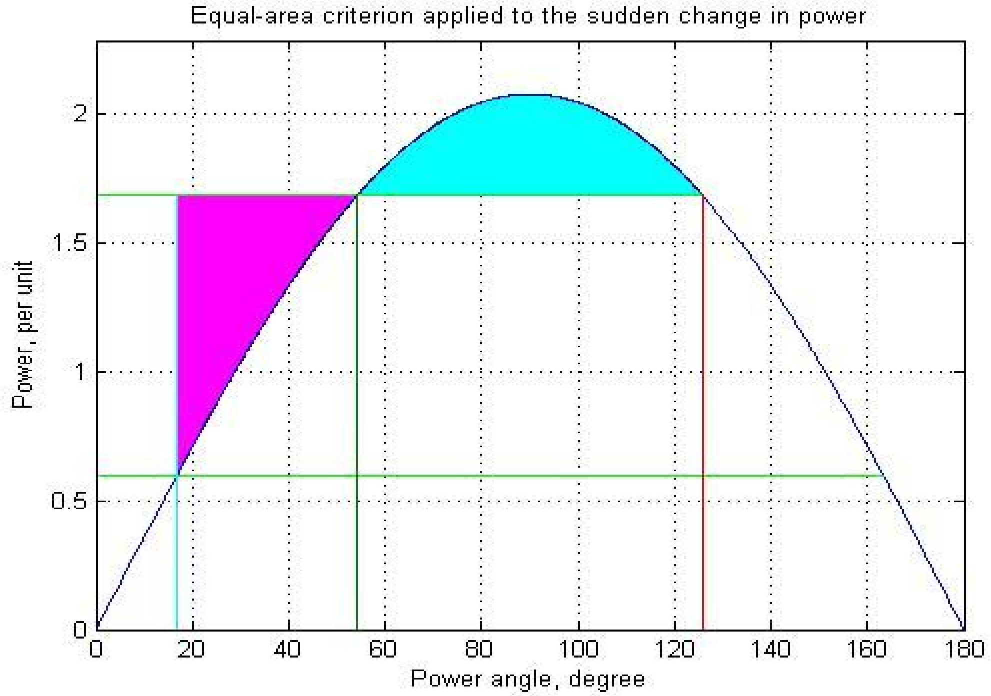


Figure 4.14: Maximum power limit by equal area criterion for maximum power input that can be applied without loss of synchronism.

For the simulation on 4.2.2 which displays result for transient stability using equal area criterion due to sudden increase in power input.This equal area criterion is used to determine the maximum additional power Pm which can be applied for stability to be maintained. From the simulation of the result, the stability is maintained only id area A2 at least equal to A1 can be located above Pm. If area A2 is less than A1, the accelerating momentum can never be overcome. The limit of stability is determined when δmax is at the intersection of line Pm and the power angle curve for $90° < \delta < 180°$ where the value for the limit of stability from this simulation is 125.840°.

When the angle increase, the electrical power increase and when the angle reaches 54.160 degrees, the electrical power matches the new input power which is 1.684 per unit as obtained from the stability.Although, the accelerating power is zero at this particular point, the rotor will be running above synchronous speed and causing the degrees and electrical power(Pe) to continue to increase.Since mechanical power(Pm) is less than electrical power(Pe), rotor will decelerate toward synchronnous speed until $\delta = \delta$ max which in this simulation is ninety degrees. The rotor must swing the point where the total power for critical stability intersects with new operating angle until an equal amount of energy is provided by the rotating masses.

The energy provided by rotor as it decelerates back to synchronous speed will provide the area of A2 and the rotor will swing back to the point where δ is max and now the area of A1 is equal to area of A2 and this is the application of equal area criterion and for stability to be retained, the two shaded areas must be equal.

For the second part of simulation, we will try to investigate what happen when the initial power input is zero and the generator internal power remains the same with the case where the initial power input is 0.6 per unit.

The parameters needed to obtain the simulation is shown in Table 4.3 below;

Table 4.3: The important parameters for the simulation of transient stability using equal area criterion due to sudden increase in power input where the initial power input is zero

Important parameters	Value (in per unit)
Initial Power (PO)	0.0
Generator internal voltage (E)	1.35
Infinite bus bar voltage (V)	1.0
Transfer Reactance (X)	0.65

The result of the simulation is shown in Table 4.4 below;

Table 4.4: The result the simulation of transient stability using equal area criterion due to sudden increase in power input.where the initial power input is zero per unit

Parameters	Value
Initial power	0.000 per.unit
Initial power angle	0.000 degrees
Sudden additional power	1.505 per unit
Total power for critical stability	1.505 per.unit
Maximum angle swing	133.563 degrees
New operating angle	46.437 degrees

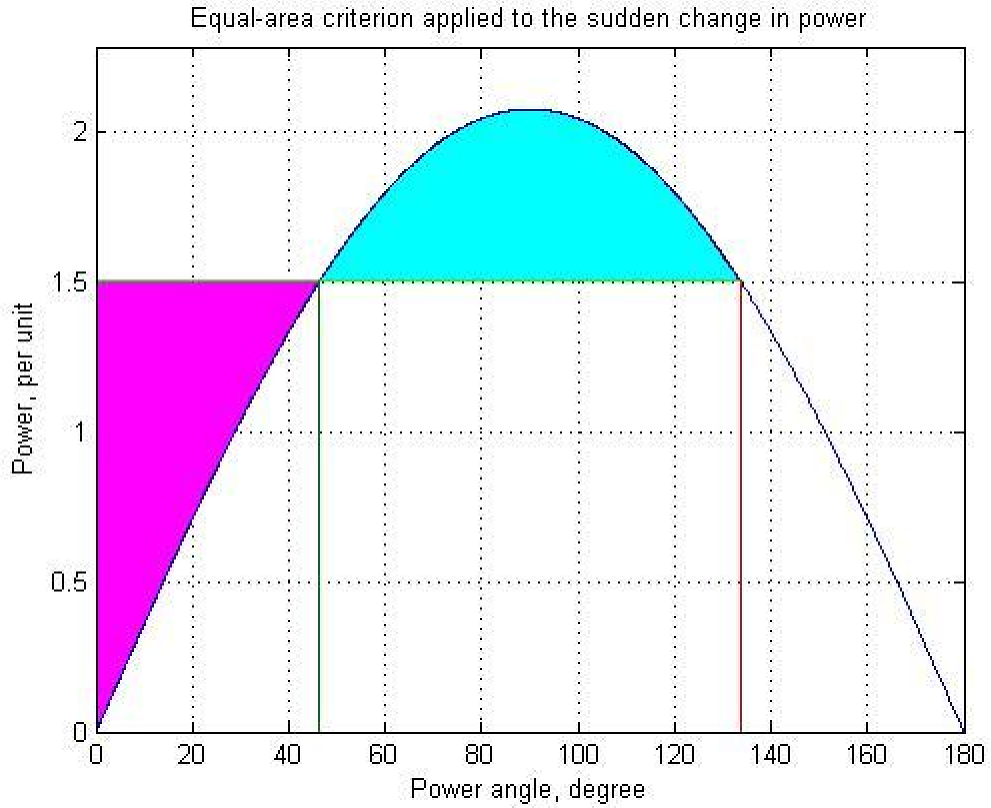


Figure 4.15: Maximum power limit by equal area criterion for zero initial power input

From the result, we can compare that when zero initial power input is applied, the equal area criterion starts the area A1 from the value of zero initial power input but when 0.6 per unit initial power input is applied, the area for A1 starts from 0.6 per unit initial power input.When the angle increase, the electrical power increase and when the angle reaches 46.437 degrees, the electrical power matches the new input power which is 1.505 per unit as obtained from the stability.

Although, the accelerating power is zero at this particular point, the rotor will be running above synchronous speed and causing the degrees and electrical power(Pe) to continue to increase.Since mechanical power(Pm) is less than electrical power(Pe), rotor will decelerate toward synchronnous speed until δ= δ max which in this simulation is ninety degrees. The rotor must swing the point where the total power for critical stability intersects with new operating angle until an equal amount of energy is provided by the rotating masses. The energy provided by rotor as it decelerates back to synchronous speed will provide the area of A2 and the rotor will swing back to the point where δ is max and now the area of A1 is equal to area of A2 and this is the application of equal area criterion and for stability to be retained, the two shaded areas must be equal.

4.2.6 Result For Transient Stability Using Equal Area Criterion Due To Three Phase Fault

In this part, the author will describe the usage of equal area criterion due to three phase fault for two case where in case A, a temporary three phase fault occurs at the sending end of the line and for case B, a three phase fault occurs at the middle of one of the lines

The Case Study used for this simulation is Case Study A where a 60-Hz synchronous generator having inertia constant H = 5 MJ/MVA and a direct axis transient reactance X'd = 0.3 per unit is connected to an infinite bus through a purely reactive circuit as shown in Figure 4.16 below. The reactances are marked on the one line diagram. The generator is delivering real power Pe= 0.8 per unit and Q = 0.074 per unit to the infinite bus at a voltage of V =1 per unit. Therefore, the critical clearing angle and the critical fault clearing time is determined when a temporary three phase fault occurs at the sending end of the line at point F where when the fault is cleared, both lines are intact

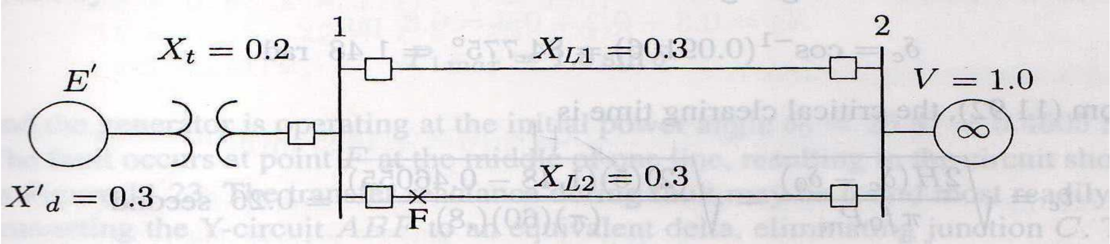


Figure 4.16: One line diagram for Case A [1]

The parameters needed to obtain the simulation is shown in Table 4.5 below;

Table 4.5: The important parameters for the simulation of transient stability using equal area criterion due to three phase fault where the fault is at the sending end of the line at point F

Parameters	Value
Initial Power (Pm)	0.8 per unit
Transient Internal Voltage (E)	1.17 per unit
Infinite Bus Bar Voltage (V)	1.0 per unit
Transfer Reactance Before Fault (X1)	0.65 per unit
Transfer Reactance During Fault (X2)	inf
Post Fault Transfer Reactance (X3)	0.65 per unit
Inertia Constant, H (Enter 0 to skip)	5

The result obtained from the simulation is shown in Table 4.6 below;

Table 4.6: The result from the simulation of transient stability using equal area criterion due to three phase fault where the fault is at the sending end of the line at point F

Parameters	Value
Initial power angle	26.388 degrees
Maximum angle swing	153.612 degrees
Critical clearing angle	84.775 degrees
Critical clearing time	0.260 sec.

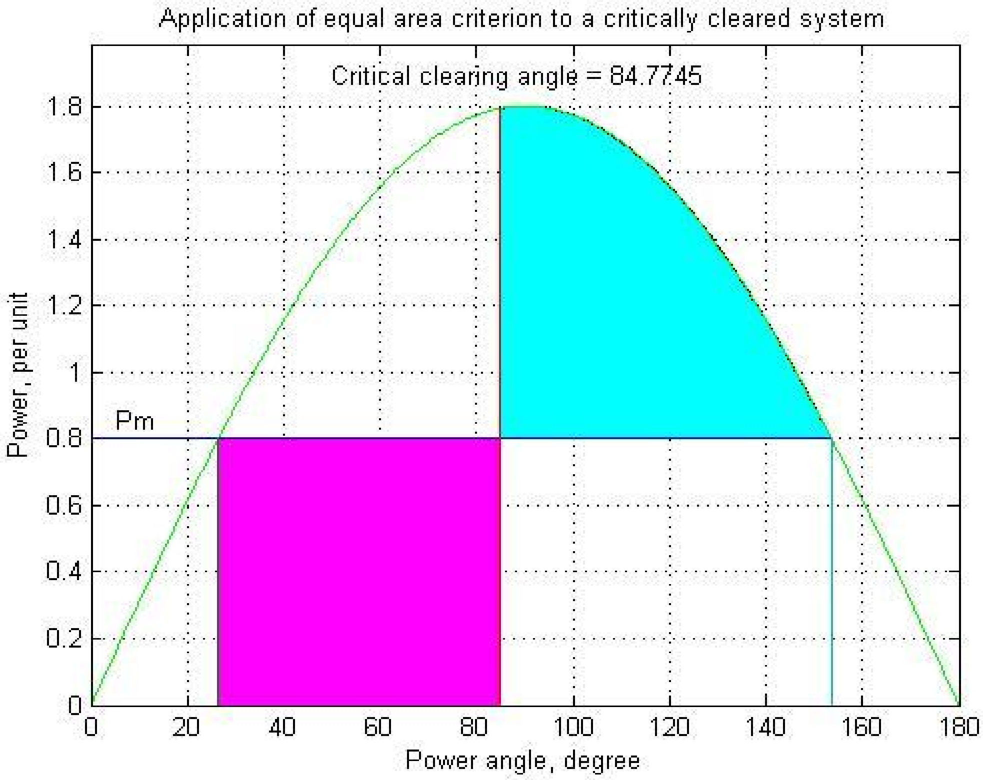


Figure 4.17: Equal area criterion for a temporary three phase fault occurs at the sending end of the line at point F,where,when the fault is cleared, both lines are intact.

Then , the simulation on 4.2.3 which displays the result when there is a temporary three phase fault occurs at the sending end of the line at point F and when the fault is cleared, both lines are intact and the simulation is done to determine the critical clearing angle and the critical fault clearing time. The simulation is based on the Figure 4.16 where the machine of the steady state example is delivering a real power of 0.6 p.u, at 0.8 power factor lagging to the infinite bus bar and the infinite bus bar voltage is 1.0 p.u. The maximum power input that can be applied without loss of synchronism is determined where it is assume the transfer reactance and the generator internal voltage were X =0.65 p.u and E' = 1.35 p.u

When the fault is at sending end of the line which in this case is Point F, there is no power transmitted to the infinite bus. Electrical power,Pe is also zero since resistances are neglected resulting the power angle curve corresponds to the horizontal axis.The angle δ increased because the kinetic energy and speed increased due to the machine acclerates with the total input power.

Critical clearing angle is found when any further increase in δ_1 causes the area A2 representing decelerating energy to become less than the area that represent the accelerating energy Therefore, critical clearing angle happens when δ_{max} is at the intersection of line represents mechanical power,Pm and curve that represents electrical power,Pe.The critical clearing angle result from this simulation is 84.775 degrees which can be found using the application of equal area criterion.The critical clearing time can be found directly using this software by just entering the inertia constant, H value which in this simulation, the critical clearing time is 0.260 second but we also can calculate the critical clearing time by solving the non linear swing equation but for direct method, we use the formula of

$$\text{Critical clearing time,}(t_c) = \left(\frac{2H(\delta_C - \delta_O)}{\Pi f_0 Pm}\right)^{1/2} \qquad (8)$$

where t_c is Critical Clearing Time, H is Inertia Constant, δ_C is critical clearing angle, δo is initial power angle,fo is frequency and Pm is input power.

The Case Study used for this simulation is Case Study B where a 60-Hz synchronous generator having inertia constant H = 5 MJ/MVA and a direct axis transient reactance X'd = 0.3 per unit is connected to an infinite bus through a purely reactive circuit as shown in Figure 4.16 below. The reactances are marked on the one line diagram. The generator is delivering real power Pe= 0.8 per unit and Q = 0.074 per unit to the infinite bus at a voltage of V =1 per unit. Therefore,the critical clearing angle and the critical fault clearing time is determined when a temporary three phase fault occurs at the middle of one of the line at where when the fault is cleared, both lines are intact

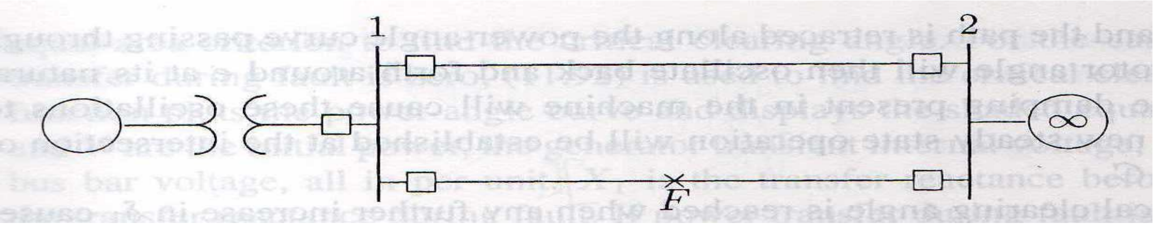


Figure 4.18: One line diagram for Case B [1]

The parameters needed to obtain the simulation is shown in Table 4.5 on the next page.

Table 4.7: The important parameters for the simulation of transient stability using equal area criterion due to three phase fault where the fault is at the middle of one of the line

Parameters	Value
Initial Power (Pm)	0.8 per unit
Transient Internal Voltage (E)	1.17 per unit
Infinite Bus Bar Voltage (V)	1.0 per unit
Transfer Reactance Before Fault (X1)	0.65 per unit
Transfer Reactance During Fault (X2)	1.8 per unit
Post Fault Transfer Reactance (X3)	0.8 per unit
Inertia Constant, H (Enter 0 to skip)	0

The result obtained from the simulation is shown in Table 4.8 below;

Table 4.8: The result from the simulation of transient stability using equal area criterion due to three phase fault where the fault is at the middle of the line.

Parameters	Value
Initial power angle	26.388 degrees
Maximum angle swing	146.838 degrees
Critical clearing angle	98.834 degrees

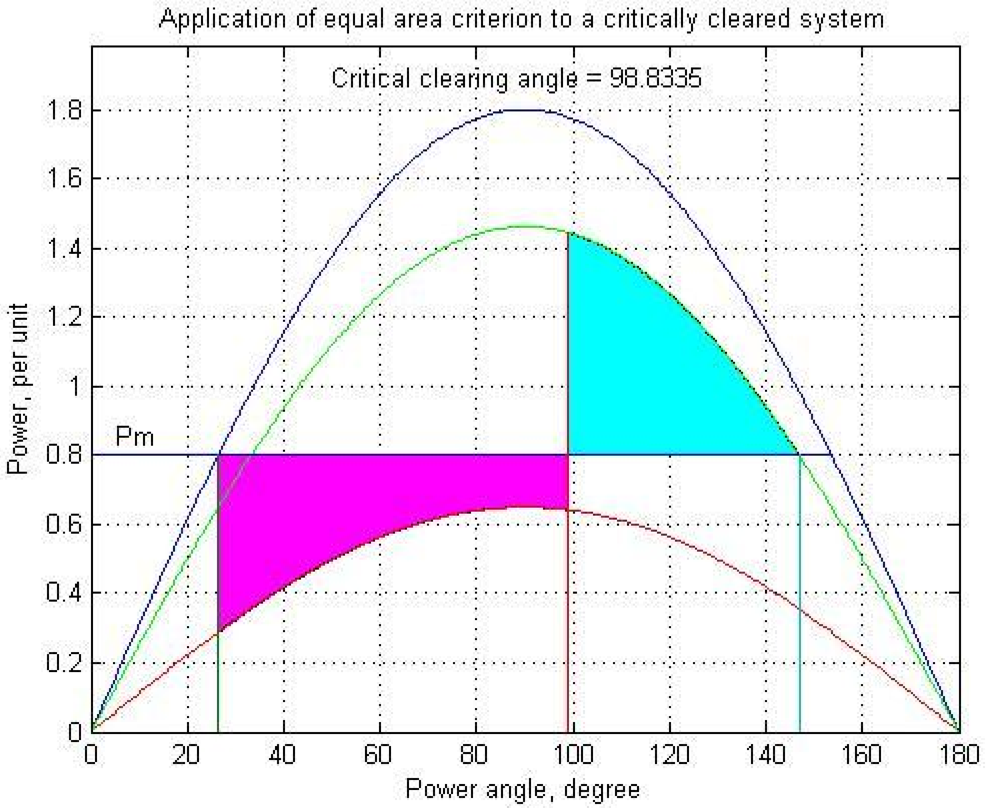


Figure 4.19: Equal area criterion for a three phase fault occurs at the middle of one of the lines, the fault is cleared and the faulted line is isolated.

The simulation for Case B which a three phase fault occurs at the middle of one of the lines, the fault is cleared and the faulted line is isolated and the critical clearing angle is determined using equal area criterion

The fault location is at the middle one of the lines. The input power Pm is assumed to be constant and the machine is operating steadily which delivers the power to the system with a power angle δ0 and this power angle curve corresponding to the prefault condition is given by curve A.

With fault location at F, away from the sending end, the equivalent transfer reactance between bus bars is increased and this will lower the power transfer capability and will result the power angle curve which is shown by the curve B which is the power angle curve during fault.

The curve C will represent the postfault power angle curve with the assumption that the faulted line is removed. When the three phase fault occurs, the operating point will be 26.388°. The excess of the mechanical input over its electrical output accelerates the rotor which cause excess kinetic energy and the angle δ increases.

When the fault is cleared at δ1 by isolating the faulted line, the net power is now deccelerating and the previously stored kinetic energy will be reduced to zero at the point where the shaded area of A2 equals the shaded area of A1.

Since Pe is still greater than Pm, the rotor continues to decelerate and the path is retrace along the power angle curve . The rotor angle will then oscillate back and forth at the natural frequency. The damping present in the machine will cause these oscillations to reduce and a new steady state operation will be produced.

The critical clearing angle is found when any further increase in δ1 causes the area A2 representing decelerating energy to become less than area A1 which represents the accelerating enery.Critical clearing angle is found by the intersection of line Pm and the after fault curve which in this simulation, the value is 98.834°.

4.2.4 Result For Simulation Of Numerical Solution Of The Swing Equation

For the simulation of the numerical solution of the swing equation, we will use the where a generator is connected to an infinite bus bar through two parallel lines where the three phase fault at the middle of one line is cleared by isolating the faulted circuit simultaneously at both ends.

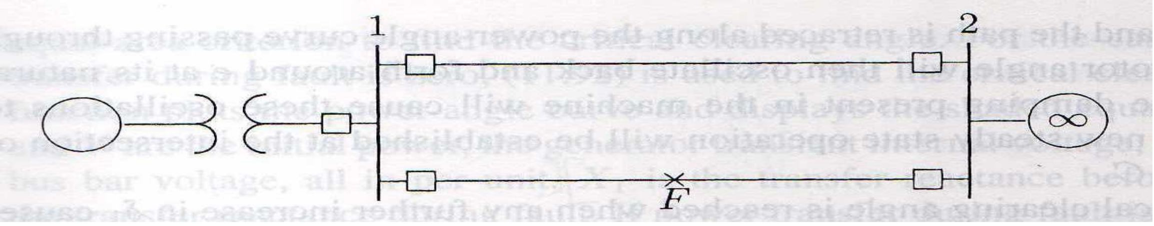


Figure 4.20: One line diagram for the simulation of the numerical solution of the swing equation [1]

Therefore, in this simulation, there will be two case where the author will try to obtain the numerical solution of the swing equation for one second using the modified Euler method with the step size of 0.100 second for fault that is cleared in 0.3 second and 0.5 second

For case where fault is cleared in 0.3 second,the input parameter is as shown in Table 4. 9 on the next page

Table 4.9: The important parameters for the simulation of of the numerical solution of the swing equation for fault cleared in 0.3 second

Parameters	Value
Initial Power (Pm)	0.80 per unit
Transient Internal Voltage (E)	1.17 per unit
Infinite Bus Bar Voltage (V)	1.0 per unit
Transfer Reactance Before Fault (X1)	0.65 per unit
Transfer Reactance During Fault (X2)	1.80 per unit
Post Fault Transfer Reactance (X3)	0.80 per unit
Inertia Constant, H (Enter 0 to skip)	5
Frequency (f)	60 Hz
Fault clearing time(tc)	0.3 second
Specified final time (tf)	1.0 second
Step size (Dt)	0.01 second

Therefore, the result is as shown in table 4.10 below where the simulation has the final time of 0.80 second

Table 4.10: The result from the simulation of swing plot when fault is cleared at 0.3 second

Result Parameter	Value
Critical clearing time	0.41 seconds
Critical clearing angle	98.83 degrees

The simulation of the swing curve for fault cleared at 0.3 second is as shown in Figure 4.19 below;

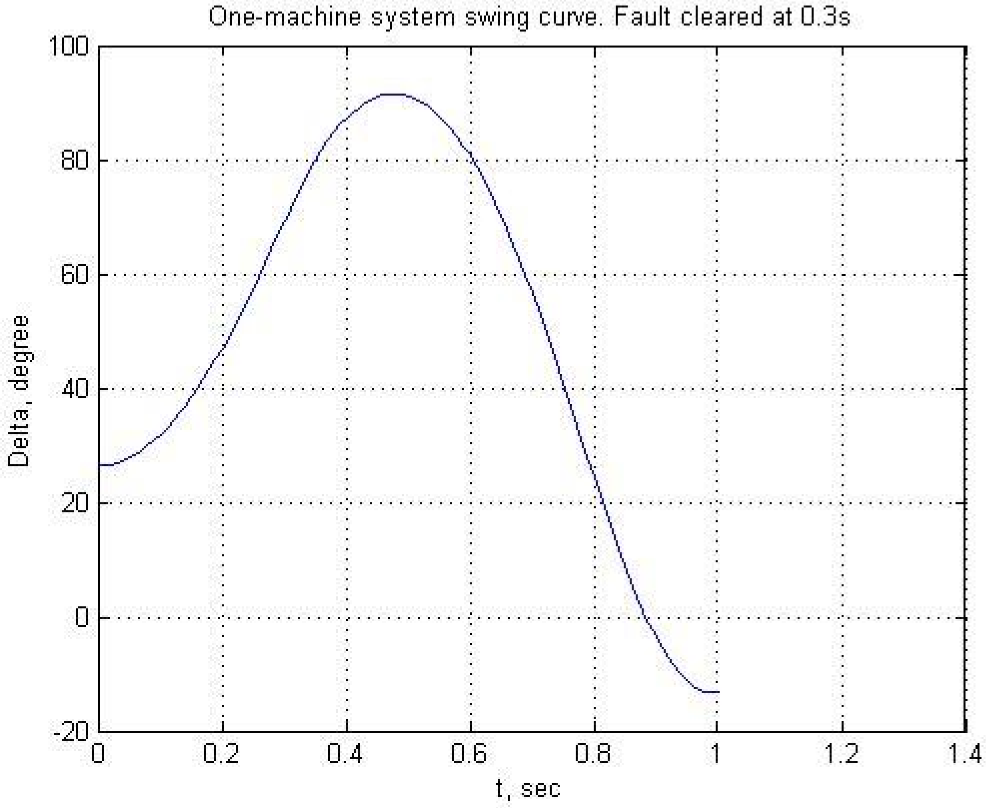


Figure 4.21: Swing curve for fault cleared at 0.3 second

The importance of numerical solution is it is possible to find the analytical solution for critical clearing time where the application of equal area criterion only gives the critical clearing angle to maintain stability.In this simulation, the numerical solution is calculated using Euler method although there are other different method such as Runge-Kutta method.

The process of finding the derivative is continued for the succesive steps which is in 0.01 second until t is 0.3 second which is the time when fault is cleared. and the process is continued with new accelerating equation until specified final time,tf =1.0

second.The time interval where the unit is second and the corresponding power angle which is in degrees and the speed deviation which is in rad/sec are displayed in the form of a table which can be found in Appendix B.

The swing curve shows that the power angle returns after a maximum swing which indicates that with the inclusion of system damping, the oscillations will reduce and a new operating angle is achieved.Therefore, the simulation of the swing curve for fault cleaed at 0.3 second shows that the critical clearing time is 0.4 second and the critical clearing angle is 98.83 degress.

For the fault clearing time of 0.5 second, the simulation is repeated using the same input parameters and the swing plots for the critical clearing time was obtained With a final time of 0.80 seconds,the result is as shown in Table 4.11 below;

Table 4.11: The result from the simulation of swing plot when fault is cleared at 0.5 second

Result Parameter	Value
Critical clearing time	0.41 seconds
Critical clearing angle	98.83 degrees

.

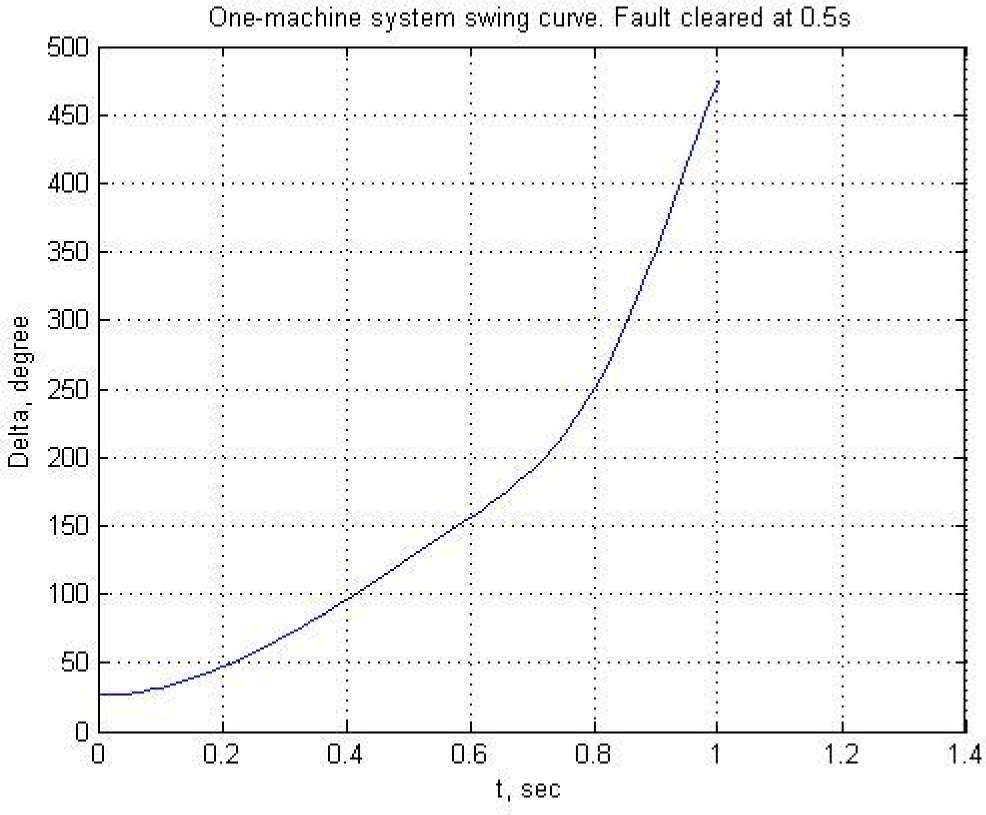


Figure 4.22: Swing curve for fault cleared at 0.5 second

For the fault clearing time of 0.4 second, the simulation is repeated using the same input parameters and the swing plots for the critical clearing time was obtained With a final time of 0.80 seconds,the result is as shown in Table 4.12 below;

Table 4.12: The result from the simulation of swing plot when fault is cleared at 0.4 second

Result Parameter	Value
Critical clearing time	0.41 seconds
Critical clearing angle	98.83 degrees

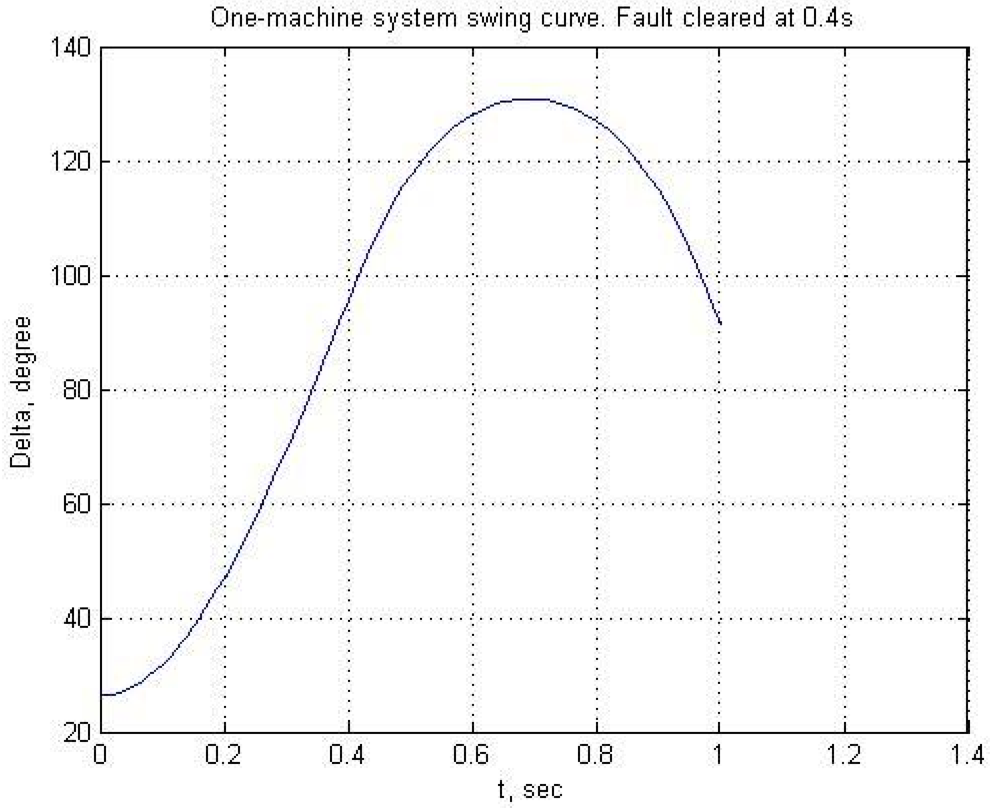


Figure 4.23: Swing curve for fault cleared at 0.4 second

From the swing curve, we can see that the swing curve for fault clearing time for 0.4 second corresponds to the critical clearing time but for fault clearing time of 0.5 second, the power angle (δ) keep on incresing without any limit.Therefore, we can conclude that the system is not stable for the clearing time of 0.5 second

4.2.5: Result For Multimachine Transient Stability

Case A:

The power system network of an electric utility company is shown in Figure 4.22. The load data and voltage magnitude, generation schedule and the reactive power limits for the regulated bases are shown below.Bus 1, whose voltage is specified as V1=1.06 /_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 in the figure below.

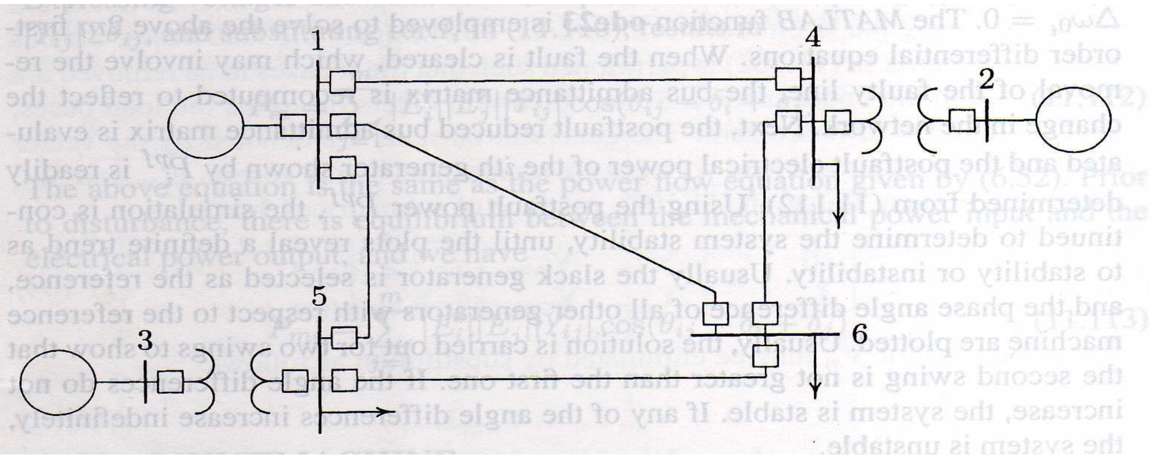


Figure 4.24: One line diagram for simulation of multimachine transient stability [1]

Table 4.13: Load Data

Bus No	Load (MW)	Load (Mvar)
1	0	0
2	0	0
3	0	0
4	100	70
5	90	30
6	160	110

Table 4.14: Generation Schedule

Bus No.	Voltage Mag.	Generation(MW)	Mvar limits Min.	Mvar limits Max.
1	1.06			
2	1.04	150	0	140
3	1.03	100	0	90

Table 4.15: Line Data

Bus No.	Bus No.	R, (per unit)	X, (per unit)	1/2B,(per unit)
1	4	0.035	0.225	0.0065
1	5	0.025	0.105	0.0045
1	6	0.040	0.215	0.0055
2	4	0.000	0.035	0.0000
3	5	0.000	0.042	0.0000
4	6	0.028	0.125	0.0035
5	6	0.026	0.175	0.0300

Table 4.16: Machine Data

Gen.	Ra	X’d	H
1	0	0.20	20
2	0	0.15	4
3	0	0.25	5

The simulation will be done first when the fault is cleared in 0.4 second where the required data is the base is 100MVA;and the accuracy is 0.0001; and the maximum iteration is 10;

Therefore, the simulation would obtain the power flow solution by Newton-Raphson method before begin the transient stability analysis where the result is shown as below:

a) Maximum Power Mismatch = 1.80187e-007

b) Number. of Iterations = 4

Table 4.17: Power Flow Result by Newton-Raphson method

Bus No.	Voltage Magnitude	Angle (degree)	Load (MW)	Load (Mvar)	Generation (MW)	Generation (Mvar)
1	1.060	0.000	0.000	0.00	105.287	107.335
2	1.040	1.470	0.000	0.00	150.000	99.771
3	1.030	0.800	0.000	0.00	100.000	35.670
4	1.008	-1.401	100.000	70.00	0.000	0.000
5	1.016	-1.499	90.000	30.00	0.000	0.000
6	0.941	-5.607	160.000	110.00	0.000	0.000
Total			350.000	210.000	355.287	242.776

The result for prefault reduced bus admittance matrix is as shown in Table 4.18 below;

Table 4.18: The prefault 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

When the faulted bus number is entered which is bus number 6, the faulted reduced bus admittance matrix is produced as shown in table below;

Table 4.19: The faulted bus admittance matrix

Ypf =

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.Then, the bus to bus Nos. of line to be removed is entered which is [5,6]

The result for postfault reduced bus admittance matrix is shown as in Table 4.20 below:

Table 4.20: The faulted 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

The simulation of multimachine transient stability need the the load data and line data input to find the power flow solution using Newton-Raphson method in order to form bus admittance matrix for prefault, during fault and postfault.

The clearing time of fault in second(tc) which is 0.4 second and the final simulation time in second where.tf = 1.5 and fault is cleared at 0.4 second resulting the phase angle difference of each machine with respect to the slack in degree is shown in Appendix C.The simulation of swing curve is plotted as shown in Figure 4.23.

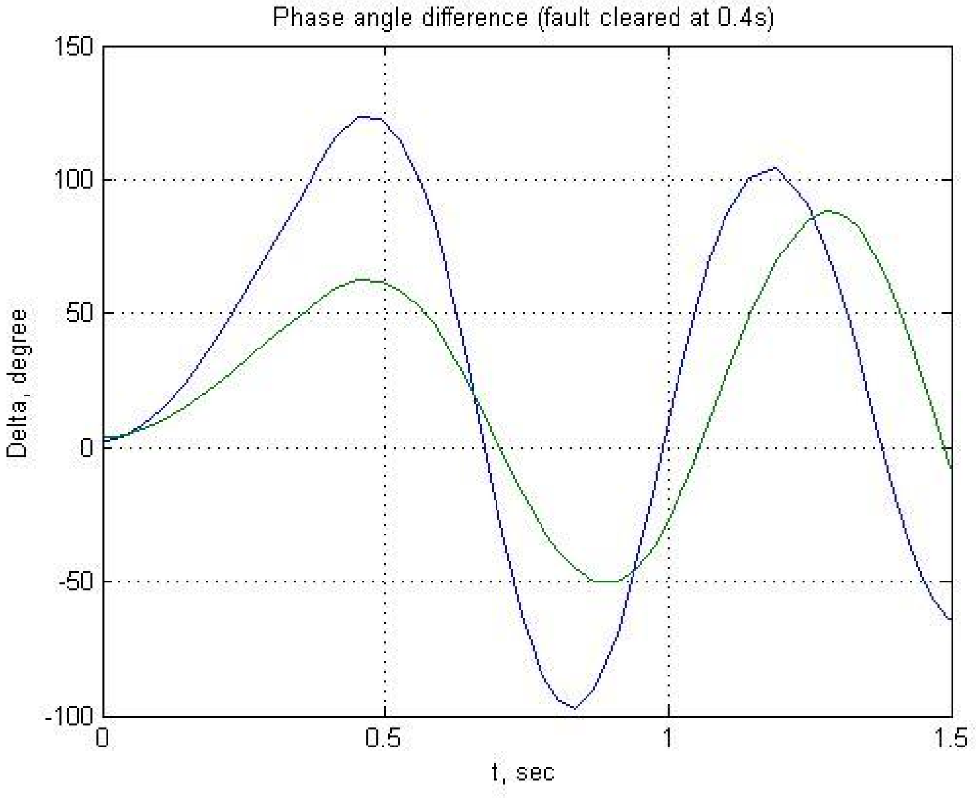


Figure 4.25: Plots of angle difference for machines 2 and 3 for fault cleared at 0.4 second

Figure 4.23 shows that the phase angle differences after reaching a maximum of 123.9 degrees and 62.95 degrees will decrease and the machines swing together.Therefore, the system is stable when fault is cleared in 0.4 second

Another clearing time of fault in second(tc) which is 0.5 second is chosen and the final simulation time in second where.tf = 1.5 and fault is cleared at 0.5 second resulting the phase angle difference of each machine with respect to the slack in degree is shown in Appendix D.The simulation of swing curve is plotted as shown in Figure 4.24.

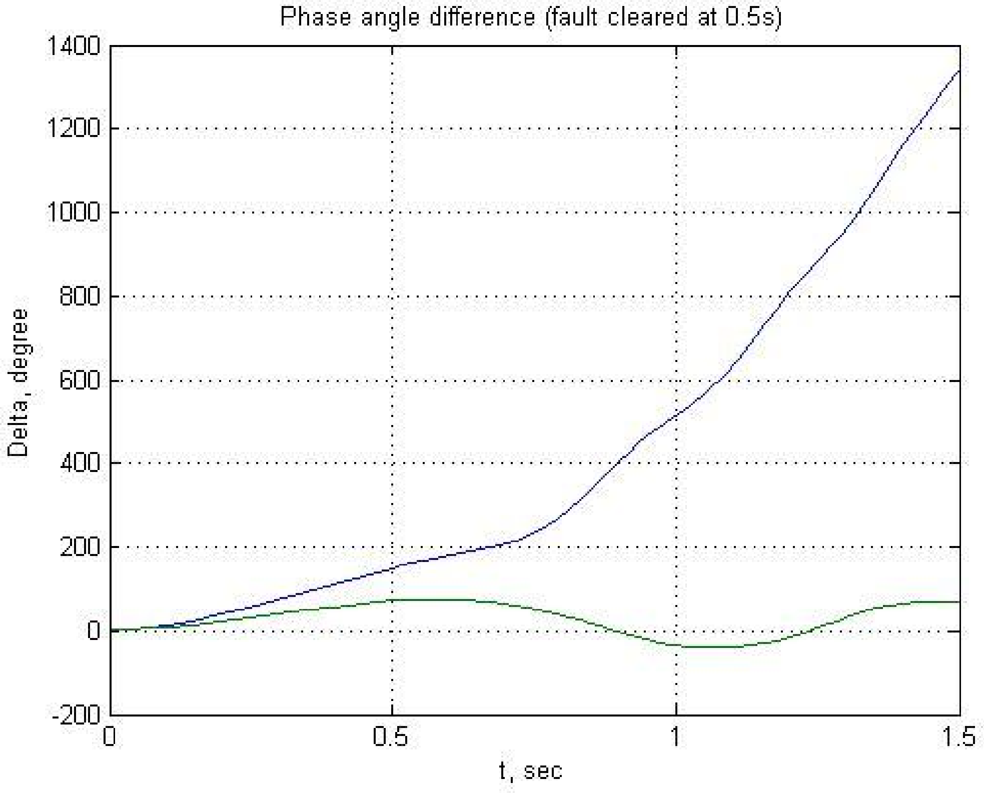


Figure 4.26: Plots of angle differences for machine 2 and 3 for fault cleared at 0.5 second

Figure 4.24 shows that when the fault is cleared in 0.5 second, the phase angle for machine 2 increases without limit and causing the system to be unstable.

Another clearing time of fault in second(tc) which is 0.45 second is chosen and the final simulation time in second where.tf = 1.5 and fault is cleared at 0.45 second resulting the phase angle difference of each machine with respect to the slack in degree.The simulation of swing curve is plotted as shown in Figure 4.25.

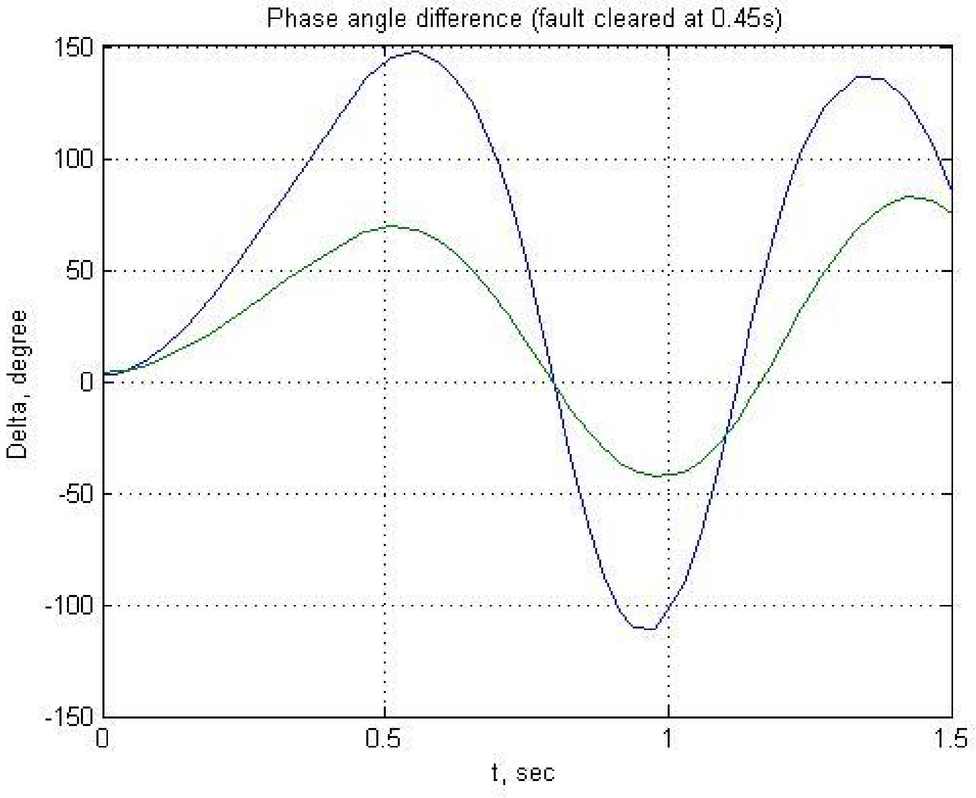


Figure 4.27: Plots of angle differences for machine 2 and 3 for fault cleared at 0.45 sec

The system is found to be critically stable when the fault is cleared in 0.45 second.

Case B:

The same load data and voltage magnitude, generation schedule and the reactive power limits for the regulated bases are used. However, a three phase fault occurs on line 1-5 near bus 5 and is cleared by the simultaneous opening of breakers at both ends of the line.

The result for prefault reduced bus admittance matrix is as shown in Table 4.21 below;

Table 4.21: The prefault 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

When the faulted bus number is entered which is bus number 5, the faulted reduced bus admittance matrix is produced as shown in table below;

Table 4.22: The faulted bus admittance matrix

Ypf =

0.2142 - 3.7380i	0.1152 + 0.5521i	0
0.1152 + 0.5521i	0.4156 - 3.2810i	0
0	0	0 - 3.4247i

The result for postfault reduced bus admittance matrix is shown as in Table 4.23 below:

Table 4.23: The faulted bus admittance matrix

Yaf =

0.3179 - 2.4304i	0.2267 + 1.2409i	0.1470 + 0.5078i
0.2267 + 1.2409i	0.5336 - 2.8465i	0.1964 + 0.5901i
0.1470 + 0.5078i	0.1964 + 0.5901i	0.3906 - 1.8015i

The simulation of multimachine transient stability need the the load data and line data input to find the power flow solution using Newton-Raphson method in order to form bus admittance matrix for prefault, during fault and postfault.

The clearing time of fault in second(tc) which is 0.2 second and the final simulation time in second where.tf = 1.5 and fault is cleared at 0.2 second resulting the phase angle difference of each machine with respect to the slack in degree.which is presented in Appendix E.The simulation of swing curve is plotted as shown in Figure 4.23.When the fault is cleared in 0.2 second

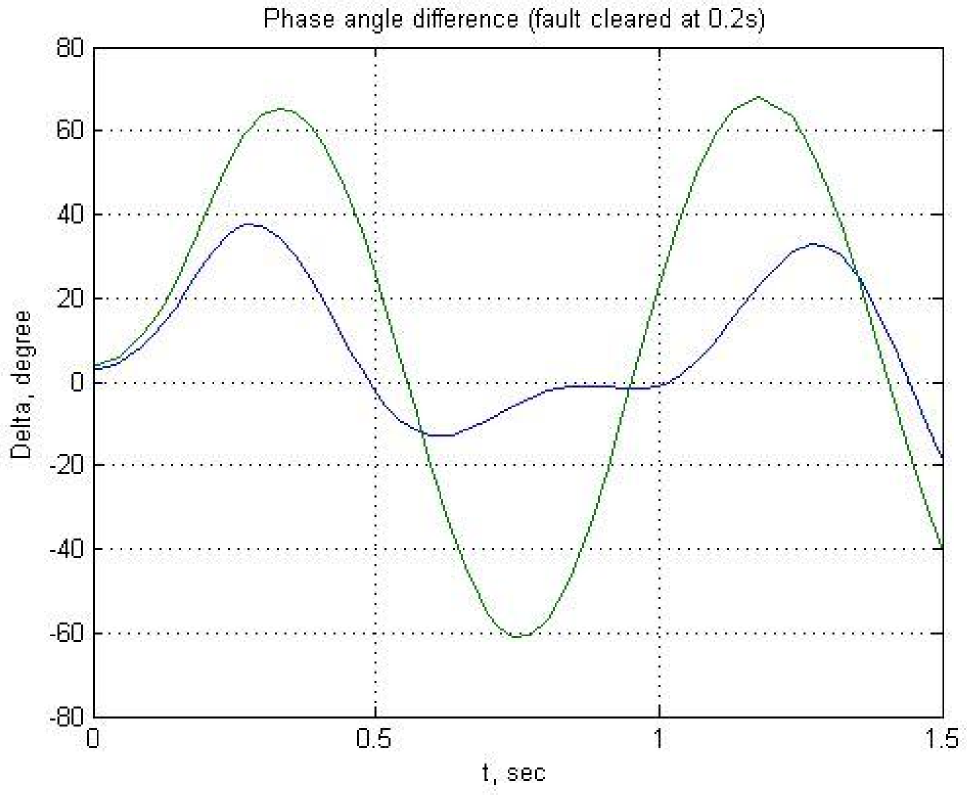


Figure 4.28: Plots of angle differences for machine 2 and 3 for fault cleared at 0.2 sec

The clearing time of fault in second(tc) which is 0.4 second and the final simulation time in second where.tf = 1.5 and fault is cleared at 0.4 second resulting the phase angle difference of each machine with respect to the slack in degree.which .The simulation of swing curve is plotted as shown in Figure 4.27 when the fault is cleared in 0.4second

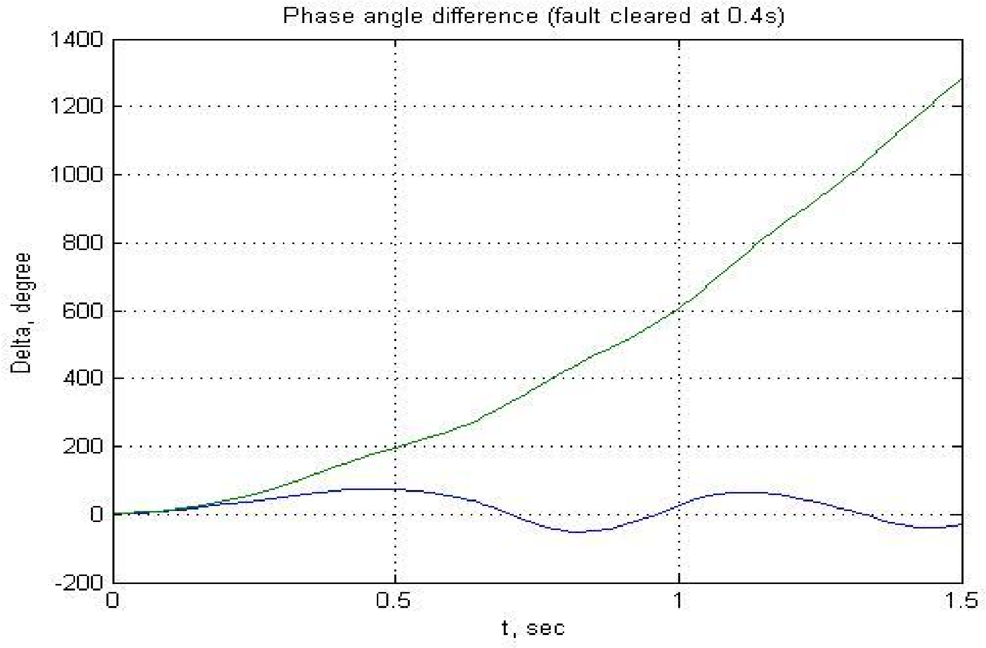


Figure 4.29: Plots of angle difference for machines 2 and 3 for fault cleared at 0.4 second

Figure 4.27 shows that when the fault is cleared in 0.4 second, the phase angle for machine 2 increases without limit and causing the system to be unstable.

Another clearing time of fault is chosen where the clearing time of fault in second tc is 0.29 second and the final simulation time in second where tf is 1.5 second. The resulting phase angle difference of each machine with respect to the slack in degree.is presented in Appendix F .The simulation of swing curve is plotted as shown in Figure 4.28 when the fault is cleared in 0.29 second

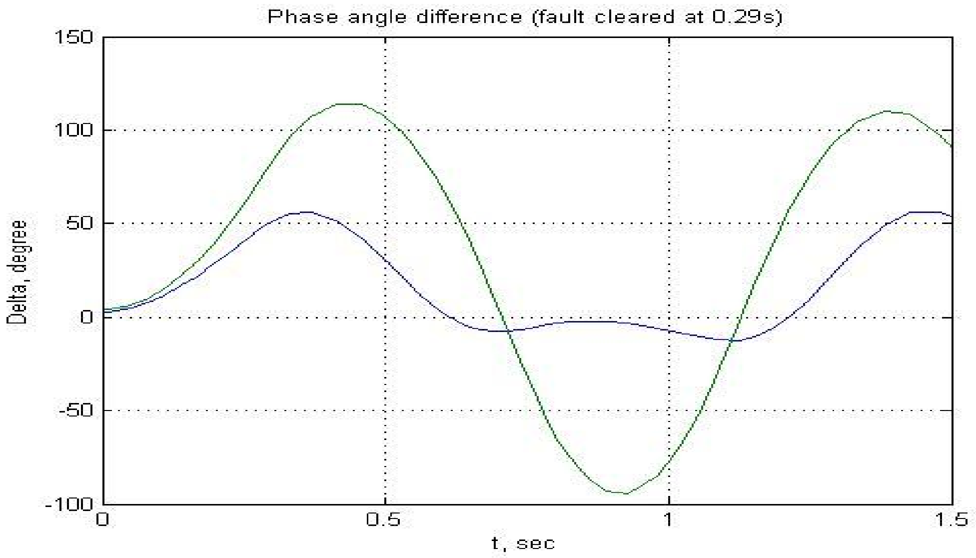


Figure 4.30: Plots of angle difference for machines 2 and 3 for fault cleared at 0.29 second

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In this project, the objective of this project which are to study and analyze the effect of small and large disturbances or fault occurrence on the power system, to obtain the simulation of steady state and transient stability studies using MATLAB and to build a user friendly software package using MATLAB GUI for education and training of steady state and transient stability studies is achieved as shown in the Chapter 4 which describe the result and simulation of the steady state and transient stability using MATLAB and also the development of user friendly software package using MATLAB GUI for education and training of steady state and transient stability studies.

5.2 Future Recommendation

The author of this project would suggest that for the future development of this project, the developer would build the programming of the stability analysis toolbox using C programming or other programming software to ensure the avalability of this toolbox in other types of programming software.

The author would also like to recommend that for the future development of this toolbox, the future developer would try to combine the SIMULINK model with this toolboxto model the stability simulation so that it woud be more fun and interactive for user to explore this toolbox.

Then, the multimachine transient stability should be improved where it can produce the output of prefault,fault and postfault bus admittance matrix in Graphical User Interface so that the output would not come out in command window.

The author like to also recommend that this toolbox can be combined with other types of toolbox in power system analysis such as power flow analysis software package, fault analysis and optimal power flow so that it will be easier for user to explore and use the whole toolbox of power system analysis.

This toolbox can also be modifed into Bahasa Melayu or combine with English so that the user that who do not understand English very well can understand this toolbox using Bahasa Melayu.

The simulation result of the toolbox should have the legend or indication on what the particular details is all about so that user can directly understands the simulation result.

5.2.1 Costing And Commercialization

The project is developed using MATLAB software packages. This software can be used for steady state and transient stability training in educational institutes such as universities or colleges or polytechnics as one part of their teaching modules which can create interest among students. This project can also be sell to engineering companies that involve in stability analysis so that this toolbox can help them to calculate the required parameters for their power system planning and requirements.

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APPENDICES

APPENDIX A

Programming of Steady State Stability-Small Disturbances Using Initial Function

Steady state simulation-small disturbances using initial function

```
>> 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 \circ')
>> subplot(2,1,2), plot(t, f), grid
>> xlabel('t, sec'), ylabel('f, Hz'), subplot(111)
```

APPENDIX B

Result of the time interval , the corresponding power angle and the speed deviation from the simulation of the swing curve for fault cleared at 0.3 second

Fault is cleared at 0.300 Sec.

time s	delta degrees	Dw rad/s
0	26.3878	0
0.0100	26.4430	0.1927
0.0200	26.6085	0.3849
0.0300	26.8841	0.5764
0.0400	27.2689	0.7665
0.0500	27.7624	0.9550
0.0600	28.3632	1.1414
0.0700	29.0703	1.3254
0.0800	29.8820	1.5065
0.0900	30.7966	1.6844
0.1000	31.8121	1.8588
0.1100	32.9265	2.0293
0.1200	34.1374	2.1956
0.1300	35.4424	2.3575
0.1400	36.8389	2.5146

0.1500	38.3240	2.6669
0.1600	39.8948	2.8140
0.1700	41.5485	2.9558
0.1800	43.2819	3.0922
0.1900	45.0918	3.2230
0.2000	46.9752	3.3483
0.2100	48.9287	3.4681
0.2200	50.9492	3.5822
0.2300	53.0336	3.6908
0.2400	55.1785	3.7939
0.2500	57.3810	3.8918
0.2600	59.6381	3.9845
0.2700	61.9469	4.0722
0.2800	64.3046	4.1553
0.2900	66.7085	4.2340
0.3000	69.1564	4.3086
0.3100	71.5638	4.0909
0.3200	73.8442	3.8661
0.3300	75.9940	3.6353
0.3400	78.0101	3.3997
0.3500	79.8899	3.1602
0.3600	81.6315	2.9176
0.3700	83.2333	2.6727
0.3800	84.6941	2.4260
0.3900	86.0133	2.1781

0.4000	87.1900	1.9293
0.4100	88.2241	1.6800
0.4200	89.1152	1.4304
0.4300	89.8632	1.1807
0.4400	90.4681	0.9309
0.4500	90.9300	0.6812
0.4600	91.2487	0.4316
0.4700	91.4245	0.1820
0.4800	91.4573	-0.0676
0.4900	91.3470	-0.3172
0.5000	91.0938	-0.5668
0.5100	90.6975	-0.8165
0.5200	90.1582	-1.0662
0.5300	89.4757	-1.3160
0.5400	88.6502	-1.5656
0.5500	87.6816	-1.8151
0.5600	86.5702	-2.0642
0.5700	85.3163	-2.3125
0.5800	83.9203	-2.5599
0.5900	82.3829	-2.8057
0.6000	80.7052	-3.0494
0.6100	78.8886	-3.2905
0.6200	76.9347	-3.5280
0.6300	74.8458	-3.7611
0.6400	72.6248	-3.9888

0.6500	70.2751	-4.2099
0.6600	67.8007	-4.4232
0.6700	65.2065	-4.6272
0.6800	62.4984	-4.8205
0.6900	59.6827	-5.0016
0.7000	56.7671	-5.1687
0.7100	53.7599	-5.3201
0.7200	50.6707	-5.4542
0.7300	47.5099	-5.5693
0.7400	44.2889	-5.6636
0.7500	41.0200	-5.7355
0.7600	37.7165	-5.7835
0.7700	34.3926	-5.8064
0.7800	31.0630	-5.8027
0.7900	27.7431	-5.7717
0.8000	24.4491	-5.7125
0.8100	21.1971	-5.6246
0.8200	18.0037	-5.5077
0.8300	14.8856	-5.3620
0.8400	11.8593	-5.1876
0.8500	8.9409	-4.9853
0.8600	6.1464	-4.7558
0.8700	3.4911	-4.5001
0.8800	0.9895	-4.2197
0.8900	-1.3446	-3.9160

0.9000	-3.4982	-3.5907
0.9100	-5.4595	-3.2456
0.9200	-7.2176	-2.8827
0.9300	-8.7630	-2.5039
0.9400	-10.0872	-2.1115
0.9500	-11.1830	-1.7076
0.9600	-12.0443	-1.2945
0.9700	-12.6667	-0.8744
0.9800	-13.0466	-0.4495
0.9900	-13.1821	-0.0223
1.0000	-13.0725	0.4051

APPENDIX C

Phase angle difference of each machine from simulation of the multimachine transient stability due to fault is cleared at 0.4 second

Fault is cleared at 0.400 Sec.

Phase angle difference of each machine

with respect to the slack in degree.

t - sec	d(2,1)	d(3,1)
0	2.8839	4.1224
0.0000	2.8839	4.1224
0.0000	2.8839	4.1224
0.0001	2.8839	4.1224
0.0003	2.8840	4.1224
0.0015	2.8862	4.1235
0.0073	2.9399	4.1509
0.0224	3.4099	4.3908
0.0444	4.9406	5.1720
0.0723	8.2866	6.8808
0.1060	14.2907	9.9504
0.1460	23.8359	14.8373
0.1860	35.4934	20.8099
0.2260	48.6576	27.5407
0.2660	62.7474	34.6877
0.3060	77.2873	41.9274
0.3460	91.9675	48.9846

0.3860	106.6754	55.6506
0.4000	111.8343	57.8619
0.4000	111.8343	57.8619
0.4117	115.7711	59.5250
0.4514	123.3461	62.7084
0.4910	122.4353	62.1741
0.5246	114.9564	58.8080
0.5571	101.5237	53.0062
0.5707	93.9706	49.8307
0.5843	85.2511	46.2219
0.5992	74.3703	41.7856
0.6151	61.2586	36.5099
0.6315	46.3109	30.5474
0.6484	29.6213	23.8982
0.6665	10.9104	16.3713
0.6874	-11.0636	7.2886
0.7076	-31.4452	-1.5650
0.7277	-50.0888	-10.2773
0.7453	-64.3270	-17.5845
0.7605	-74.7647	-23.5451
0.7728	-81.8172	-28.0628
0.7869	-88.2825	-32.8413
0.8064	-94.3483	-38.6949
0.8333	-97.0931	-45.0843
0.8705	-90.1891	-50.2025

0.9099	-70.0025	-50.2533
0.9431	-44.2898	-45.5321
0.9756	-14.0114	-36.4903
1.0106	19.9645	-22.2399
1.0438	49.4313	-5.4158
1.0726	70.6234	10.6518
1.1035	87.7813	28.1804
1.1415	100.5913	48.4869
1.1896	103.9511	69.7127
1.2444	90.9792	84.8240
1.2773	75.0434	88.1302
1.2974	62.6822	87.7623
1.3174	48.6144	85.5064
1.3345	35.5322	82.0560
1.3498	23.3208	77.8011
1.3651	10.8942	72.4688
1.3850	-5.1516	63.9678
1.4059	-21.0700	53.3371
1.4268	-35.3195	41.1849
1.4478	-47.3380	27.7068
1.4706	-57.1182	12.1591
1.4960	-63.5779	-5.6903
1.5000	-64.1454	-8.4713

APPENDIX D

Phase angle difference of each machine from simulation of the multimachine transient stability due to fault is cleared at 0.5 second

```
Fault is cleared at 0.500 Sec.

Phase angle difference of each machine

with respect to the slack in degree.

   t - sec    d(2,1)    d(3,1)

  1.0e+003 *

        0    0.0029    0.0041
   0.0000    0.0029    0.0041
   0.0000    0.0029    0.0041
   0.0000    0.0029    0.0041
   0.0000    0.0029    0.0041
   0.0000    0.0029    0.0041
   0.0000    0.0029    0.0042
   0.0000    0.0034    0.0044
   0.0000    0.0049    0.0052
   0.0001    0.0083    0.0069
   0.0001    0.0143    0.0100
   0.0001    0.0240    0.0149
   0.0002    0.0387    0.0225
   0.0002    0.0557    0.0311
   0.0003    0.0737    0.0402
```

0.0003	0.0920	0.0490
0.0004	0.1104	0.0573
0.0004	0.1291	0.0647
0.0005	0.1503	0.0716
0.0005	0.1503	0.0716
0.0005	0.1572	0.0734
0.0006	0.1738	0.0754
0.0006	0.1861	0.0730
0.0007	0.1997	0.0671
0.0007	0.2163	0.0593
0.0008	0.2389	0.0500
0.0008	0.2674	0.0400
0.0008	0.2889	0.0331
0.0008	0.3137	0.0254
0.0008	0.3362	0.0185
0.0009	0.3570	0.0120
0.0009	0.3789	0.0052
0.0009	0.4034	-0.0027
0.0009	0.4265	-0.0101
0.0009	0.4457	-0.0162
0.0009	0.4645	-0.0219
0.0010	0.4843	-0.0274
0.0010	0.5072	-0.0327
0.0010	0.5374	-0.0374
0.0011	0.5729	-0.0397

0.0011	0.6061	-0.0399
0.0011	0.6451	-0.0385
0.0011	0.6853	-0.0355
0.0012	0.7332	-0.0298
0.0012	0.7731	-0.0231
0.0012	0.8105	-0.0148
0.0012	0.8456	-0.0052
0.0012	0.8834	0.0067
0.0013	0.9326	0.0226
0.0013	0.9720	0.0340
0.0013	1.0159	0.0446
0.0014	1.0606	0.0532
0.0014	1.1117	0.0606
0.0014	1.1624	0.0657
0.0014	1.2046	0.0684
0.0014	1.2445	0.0698
0.0015	1.2883	0.0704
0.0015	1.3322	0.0702
0.0015	1.3394	0.0701

APPENDIX E

Phase angle difference of each machine from simulation of the multimachine transient stability due to fault is cleared at 0.2 second

Fault is cleared at 0.2 second

t - sec	d(2,1)	d(3,1)
0	2.8839	4.1224
0.0000	2.8839	4.1224
0.0000	2.8839	4.1224
0.0001	2.8839	4.1224
0.0003	2.8840	4.1225
0.0017	2.8860	4.1249
0.0083	2.9363	4.1860
0.0255	3.3780	4.7239
0.0455	4.4488	6.0371
0.0655	6.0987	8.0861
0.0855	8.2966	10.8657
0.1055	11.0015	14.3687
0.1255	14.1634	18.5863
0.1455	17.7251	23.5081
0.1655	21.6236	29.1226
0.1855	25.7920	35.4171
0.2000	28.9469	40.4033
0.2000	28.9469	40.4033
0.2077	30.5729	43.0824

0.2385	35.4976	52.4385
0.2693	37.7514	59.3867
0.2999	37.3233	63.6719
0.3298	34.5148	65.1961
0.3581	29.9778	64.1552
0.3849	24.4152	60.9664
0.4122	17.9008	55.5612
0.4332	12.6448	50.0108
0.4541	7.4352	43.3365
0.4736	2.8553	36.2542
0.4954	-1.7968	27.4154
0.5178	-5.8591	17.5298
0.5415	-9.2046	6.4750
0.5674	-11.6507	-5.8585
0.5968	-12.9580	-19.6671
0.6341	-12.6846	-35.5931
0.6577	-11.6837	-44.2212
0.6814	-10.2575	-51.3041
0.7004	-8.9329	-55.6957
0.7188	-7.5774	-58.7784
0.7425	-5.8567	-60.9229
0.7711	-3.9710	-60.7167
0.8044	-2.2728	-56.6214
0.8412	-1.2166	-47.5512
0.8755	-1.0174	-35.3554

0.9061	-1.3061	-22.1177
0.9365	-1.7087	-7.5798
0.9760	-1.6999	11.8740
1.0103	-0.5331	27.8781
1.0386	1.5449	39.6784
1.0672	4.7536	49.8982
1.0981	9.3188	58.5975
1.1334	15.4535	65.2382
1.1774	23.3149	68.2825
1.2342	30.9834	63.3453
1.2705	32.8650	55.1459
1.2993	32.1283	46.1381
1.3216	30.0659	37.8246
1.3372	27.8529	31.4733
1.3527	25.0192	24.7417
1.3712	20.8769	16.3287
1.3955	14.3754	4.9586
1.4219	6.2470	-7.4974
1.4392	0.5861	-15.4555
1.4566	-5.1424	-23.0932
1.4735	-10.6523	-30.1483
1.4950	-17.1986	-38.2741
1.5000	-18.6240	-40.0194

APPENDIX F

Phase angle difference of each machine from simulation of the multimachine transient stability due to fault is cleared at 0.29 second

```
Fault is cleared at 0.290 Sec.

Phase angle difference of each machine

with respect to the slack in degree.

  t - sec    d(2,1)    d(3,1)

       0    2.8839    4.1224

   0.0000    2.8839    4.1224

   0.0000    2.8839    4.1224

   0.0001    2.8839    4.1224

   0.0003    2.8840    4.1225

   0.0017    2.8860    4.1249

   0.0083    2.9363    4.1860

   0.0255    3.3780    4.7239

   0.0506    4.8156    6.4892

   0.0796    7.5945    9.9693

   0.1086   11.4647   14.9748

   0.1376   16.2764   21.4791

   0.1666   21.8483   29.4494

   0.1956   27.9791   38.8478

   0.2246   34.4598   49.6335

   0.2536   41.0867   61.7646
```

0.2826	47.6719	75.2003
0.2900	49.3302	78.8439
0.2900	49.3302	78.8439
0.2979	50.9774	82.6568
0.3310	55.5417	96.3561
0.3693	56.2321	107.3880
0.4135	51.5296	113.7505
0.4569	42.3090	113.4650
0.4921	32.5360	108.6145
0.5255	22.4009	100.2743
0.5557	13.4075	89.6623
0.5860	5.3848	76.1943
0.6060	0.9400	65.7574
0.6260	-2.6381	54.1781
0.6464	-5.3121	41.2802
0.6675	-7.0215	27.0383
0.6893	-7.7607	11.5429
0.7127	-7.5964	-5.5010
0.7407	-6.5356	-25.5503
0.7641	-5.3196	-41.4217
0.7876	-4.1147	-55.8285
0.8086	-3.2146	-67.1330
0.8261	-2.6633	-75.2050
0.8406	-2.3653	-80.8482
0.8610	-2.1924	-87.2081

0.8885	-2.4025	-92.7036
0.9267	-3.4454	-94.3476
0.9797	-6.0464	-85.0379
1.0171	-8.4114	-70.6259
1.0545	-10.7821	-50.4523
1.0871	-12.2604	-29.2990
1.1249	-12.2892	-2.4898
1.1542	-10.3612	18.4919
1.1836	-6.3446	38.4750
1.2131	-0.1671	56.7989
1.2454	8.6485	74.1474
1.2847	21.1189	90.9283
1.3324	36.3761	104.5414
1.3801	48.7947	110.4569
1.4269	55.9210	108.6230
1.4781	56.2265	97.7919
1.5000	53.7086	90.3551