T. C.

YAŞAR UNIVERSITY

GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

MASTER THESIS

STRUCTURE PRESERVING MODEL FOR ANALYSIS OF TRANSIENT STABILITY OF POWER SYSTEM

Mohammed Amer Mohammed

Thesis Advisor: Prof. Dr. Erol Sezer

Department of Electrical and Electronics Engineering

Presentation Date: 03.09.2015

İZMİR – TURKEY

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APPROVAL

This study, titled "Structure Preserving Model Transient Power System Stability" and presented as Master (Post Graduate) Thesis by Mohammed Amer Mohammed, has been evaluated in compliance with the relevant provisions of Y.U. Graduate Education and Training Regulations and Y.U. Institute of Science Education and Training Direction. The jury members below have decided for the defence of this thesis, and it has been declared by consensus / ~~majority~~ of votes that the candidate has succeeded in his thesis defence examination dated …03/09/2015

Jury Members: **Signature:**

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Member : Hacer Şekerci

Member : Nurdan Yıldırım Özcan

Prof. Dr. Behçet Gürkan (Enst. Md.)

ABSTRACT

STRUCTURE PRESERVING MODEL TRANSIENT POWER SYSTEM STABILITY

Mohammed AMER

MSc in Electrical and Electronics Engineering

Thesis Advisor: **Prof. Dr. Erol Sezer**

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An important problem in transient stability analysis of interconnected power system is determination of the effect of fault-clearing-time or stability. Classical approach to the problem is to simulate the dynamic model of the system with the help of a computer during the fault and after it is cleared. This, however, requires a different simulation for each clearings time.

An alternative approach is to use Lyapunov theory to determine a region of attraction about the stable post-fault equilibrium. In this study, a structure preserving dynamic model that enables construction of a suitable Lyapunov Function.

Keywords: Lyapunov function, transient stability, dynamic analysis, ETAP software.

ÖZET

GÜÇ SİSTEMİNİN GEÇİCİ DURUM KARARLILIK ANALİZİNDE YAPI KORUYUCU MODELİ

Mohammed AMER
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Tez Danışmanı: Prof. Dr. M. Erol SEZER
Eylül 2015, 62 sayfa

Güç sisteminin geçici durum kararlılık analizinde karşılaşılan önemli bir problem arıza temizlenme süresinin sistem kararlılığına etkisinin belirlenmesidir. Probleminin çözümü için kullanılan klasik yöntem sistemin dinamik modelinin arıza süresince ve arıza temizlendikten sonra bilgisayar aracılığıyla benzetim edilmesidir. Her bir arıza temizleme süresi için ayrı bir benzetim gerekmektedir.

Alternatif yöntem olarak, Lyapunov teorisi kullanılarak sonar sistemin arıza sonrası kararlı denge noktası etrafında bir çekim alanı belirlenmesi önerilmiştir. Bu çalışmada bu amaca yönelik bir Lyapunov fonksiyonu oluşturmak için, yapı koruyucu bir sistem modeli incelenmiştir.

Anahtar sözcükler: Lyapunov fonksiyonu, Geçici durum kararlılık
dinamik analiz, ETAP yazılım

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TABLE OF CONTENTS

INDEX OF FIGURES

INDEX OF TABLES

INDEX OF SYMBOLS

Symbols	**Explanations**
$\Delta\delta$	Rotor angle deviation.
$\Delta\omega$	Speed deviation (-)
E_b	Infinite bus (*V*)
δ	Electrical power angle (rad)
P_a	Accelerating power (air-gap machine power) (*W)*
P_m	Mechanical power acting on the rotor (*W)*
P_e	Electrical power acting on the rotor (*W)*
ω_i	Rotor speed deviation of *i*-machine (rad/s)
M_i	Inertia constant of *i*-machine
D_i	Damping coefficient of *i*-machine (load frequency coefficient)
P_{max}	Maximum electrical output (*W)*
G_{ij}	Real parts of reduce nodal admittance matrix (*S)*
B_{ij}	Imaginary parts of reduce nodal admittance matrix (*S)*
V_i, V_j	Internal voltage of machine *i*,*j* (*V*)
$\delta_{ij} = \delta_i - \delta_j$	*Internal voltage machine angle* (V_i, V_j)
$\lvert E \rvert$	Magnitude generator voltage (*V*)
V_t	Terminal voltage (*V*)
R_a	Armature resistance (*Ohm*)

I_a	Output generator current (*A*)
X'_d	Transient generator reactance (*Ohm*)
X''_d	Dynamic generator reactance (*Ohm*)
J	The total moment of inertia of the synchronous machine ($kg.m^2$)
θ_m	The mechanical angle of the rotor (*rad*)
T_m	Mechanical torque from turbine or load (*N.m*)
T_e	Electromagnetic torque on the rotor (*N.m*)
δ_m	Rotor position before disturbance at time =0 (*rad*)
H	Inertia constant (-)
$\bar{I}$	The vector injection currents node (*A*)
Y_{Bus}	The bus admittance matrix (*S*)
$\bar{V}$	The vector voltage node
E'_k	Internal machine magnitude voltage (*V*)
V_k	Load bus voltage (*V*)
σ_k	Angle across the *k*th branch (rad)

INDEX OF ABBREVIATIONS

Symbols	**Explanations**
TSP	Transient Stability Problem (-)
TSA	Transient Stability Assessment (-)
SMIB	Single Machine Infinite Bus (-)
DAE	Differential Algebraic Equations (-)

CHAPTER 1

TRANSIENT STABILITY

1.1 Introduction

Power system stability has been familiar as an important problem for secure system operation. Stable electrical system is a requirement for manufacture, rail, hospital & all sphere of life. The stability of a power system implies that all generators remain in synchronism through normal and abnormal operating conditions. Transient stability arises when a large disturbance occur such as a loss of a generator, a sudden change of load, or a transmission line fault…. etc. The increase demand of electrical energy requires a maximum or increasing electrical generation. Therefore, transient stability has become an important issue for power system planning and operation engineers.

The question is how to settle transient stability problem when the problems occur in power system network? Transient power system stability consists of obtaining the time solution of the power system differential equation starting from the system conditions to the transient case.

The operation power system conditions have been changing during the course of the day (daily load), month and year, while studies of stability are done. The off-line solutions often lead to improper results in some cases.

From the above, it is clear that the power system needs an alternative methods to solve the transient stability problem. The transient stability problem is difficult to solve as it involves a different simulation for each fault condition. Another issue is that power generation and consumption change continuously. In that case, the best solution is on-line method that deals with system operation on a real-time [1].

1.2 Transient Stability Problem (TSP)

Stability of power system has been becoming more complicated and continues to be a major concern in operating system. Over 50 years ago studies of TSPs were challenged by planners and operator engineer [2]. Power system stability is that property of a power system that have ability to remain in a stable operation of a stable equilibrium point under normal operating conditions and operating in minimum limit stable region after disturbances occur [3]. The stability problem was tied the behavior of the machines after a disturbance.

To remain in a steady state is a huge challenge during disturbances that occur in the power system. Synchronous operation of system during small or large disturbance will affect to it. If the system loss generator units, increasing load suddenly or switching due to fault occur, it will cause a problem in whole power system may be to loss synchronous operation. Stability after this disturbance determines whether the synchronous operation can be recovered to the steady state case after this transient problem [3].

The huge challenge in power system stability may be one or more of these:

- Continued demand growth load or increase demand of electrical energy requires.
- Environmental pressures on transmission expansion,
- The disturbances in a part of power system like faults occurring in one or more of units.

Power system can be prevent damage due to these disturbances by protective relays system. Power system disturbances can be view in three configuration stages:

- Pre-fault system, is a stable state because the operating system is around a stable equilibrium point, when a disturbance occurs, the system moves into the fault-on system before clearing fault.
- Fault on or during the fault.
- Post-fault.

Instability of power system may occur in many different situations depending on the fault types, system configuration and operation system. Stability in power system implies that all interconnected generators are operating in synchronism with connected to power system network. When disturbance occur in network such as transmission faults, one or more generators will lose synchronism. This problem will lead the system to unstable system. There are two types of stability problem in power systems.

1. Steady state stability problem, which refers to the stability of power systems under a small disturbance in the power system such as a rapidly change loads.

2. Transient stability problem, which refers to the stability of power systems under a large disturbance in the power system such as a generators losses suddenly, loads increase immediately, or switching operations. This disturbance will lead to unstable system and generator oscillation until recover to new steady state operating point, or rotors of generator continue oscillating until loss synchronism.

Loss of synchronism must be prevented or controlled otherwise the disturbance effect on voltage, frequency and power, so it causes:

- Damage on generator, to prevent this problem it should be protect this generator by tripped which is disconnected from the system before damage occurs, and subsequently brought back to synchronism. Generator synchronous is not readily and it take time to rebuild steam and operator has to shed load to compensate the loss of generations.
- Protective relays during loss of generator, due to the under frequency protection relay trip, or under voltage rely trip [1].

1.3 Rotor Angle Stability

Power system stability can be studied each case as a single problem, because each case has a different property in power system. In practical, analysis of stability problems is essential factors to identify contribute of instability. Classify of power system is a requirement as the first method to improve the system stable or not. Figure1.1 illustrates the power system stability problem in classes and subclasses terms [3].

Rotor angle stability is the ability of interconnected synchronous machines of power system to remain in synchronism [1]. All rotor machines in power system operating in steady state have the synchronism which refer to same rotor speed ω_0. Electromechanical oscillations are the main concept of stability problem in power system, because any change in output machine will change the rotor speed.

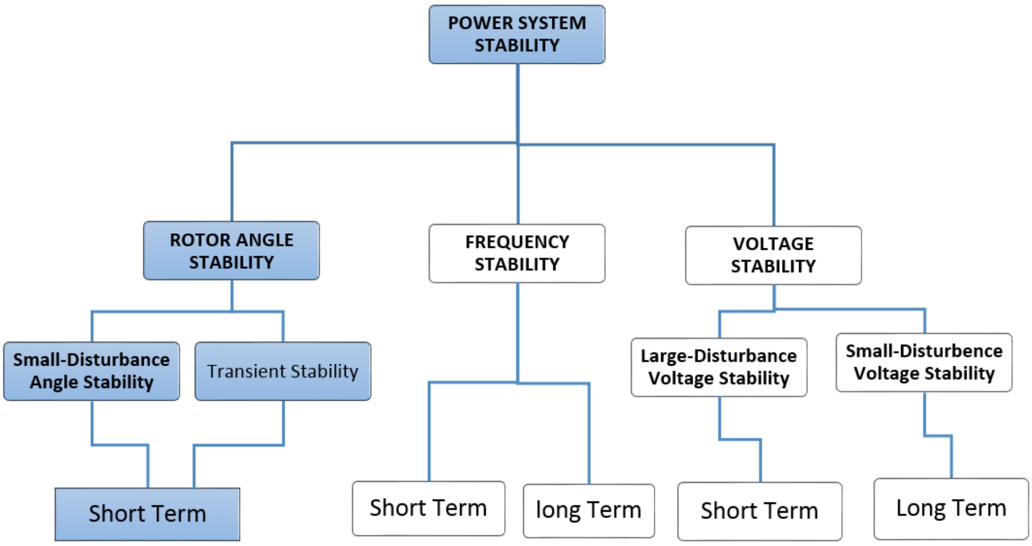

Figure 1-1 Classification of power system stability [1]

One of the synchronous operating interconnected conditions between generators is to have the same generation frequency. Therefore, all machine's rotor have the synchronism. The rotor angle will take a new position operation, after machine get a disturbance. The electrical output of generators depends on changing mechanical output, therefore, the effect of increasing or decreasing mechanical output power is lead to changing the torque on the rotor [3].

The important characteristic on power system stability is the relationship between interchange power and angular positions of synchronous machines rotors. Therefore, output power of machines is a function of angular separation (δ) between rotors when the generators are interconnected.

For example, consider the simple system shown in Figure 1.2, consists of two synchronous generators are connected through transmission line, which have inductive reactance and negligible resistance and capacitance. Figure 1.2 (b), (c) show the idealized model and phase diagram, respectively. The nonlinear relationship between the power and rotor angle is shown in Figure 1.2 (d). This example show the maximum steady-state power can be transmitted in this circuit, but if the power system have a more than generator, then all rotor angles will affect the interchange of transmit power. However, power transfer angle limitations are complex function of power system [3], [5], [6].

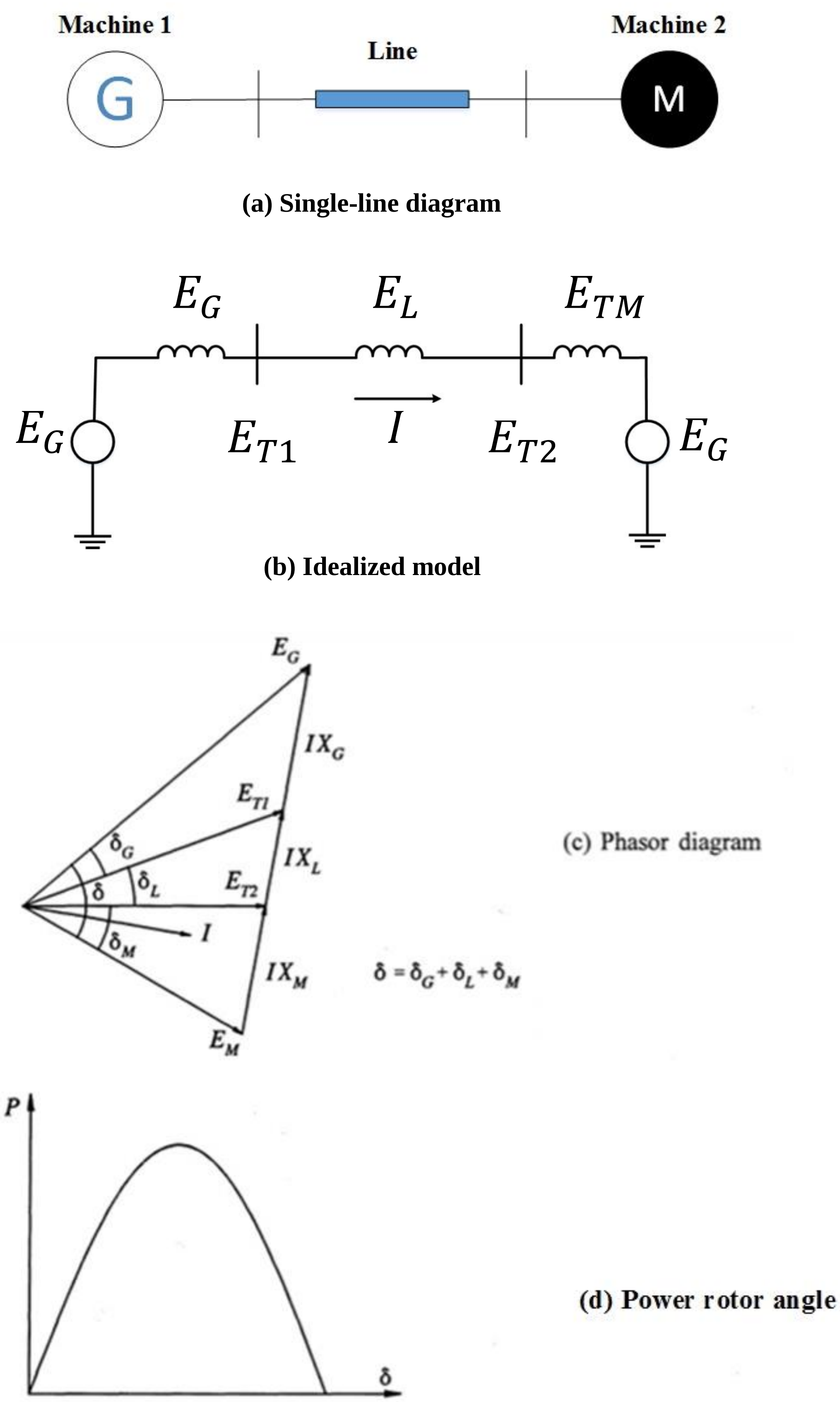

Figure 1-2 Power transfer characteristic of a two-machine system

1.4 Transient Stability

Transient stability is the ability of power system to maintain synchronism when subjected to a severe transient disturbance. Stability depends on the initial system operation and the type of disturbance severity. The behavior of rotor angle synchronous machine during the transient disturbances may lead stable or unstable situations shown by Figure1.3.

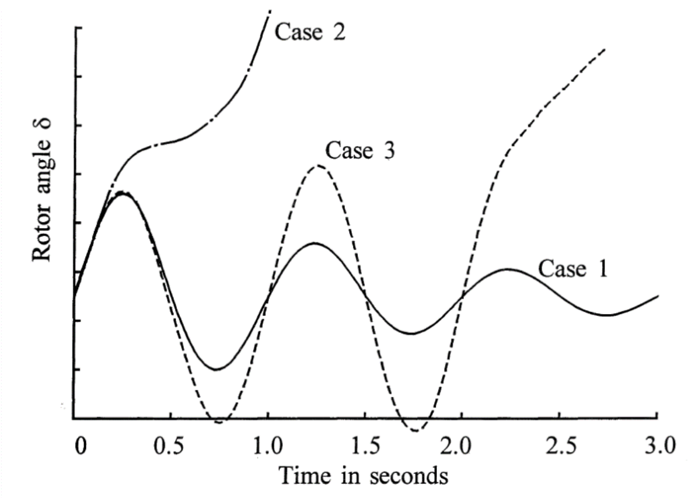

Figure 1-3 Rotor angle response to a transient disturbance

Case 1: rotor angle is increasing, but oscillations are decreasing. This case will go to stable mode because it will reach a steady-state.

Case 2: rotor angle continues increasing, and oscillations are increasing until loss of synchronism. This case will go on instability mode because of in sufficient synchronizing torque.

Case 3: rotor angle is increasing, and growing oscillations lead to unstable mode.

Instability transient in large power system may not always occur at first swing instability; it could be the result of the superposition of several modes of oscillation. The period limit of transient stability is usually between 3 to 5 seconds following the disturbance [3], [7].

1.5 Literature Review

Provides literature review on publications from IEEE conferences and student theses. It is to find available information and previous results from analysis transient stability of power system.

1. A Practical Method for Power systems transient Stability y and Security, this thesis are used Step-by-Step and Direct Method using Equal Area Criterion is analyze the transient stability, calculate the potential and kinetic energies for all machines in power system. This method are compared between the kinetic energies in large groups and small groups, this comparison lead to determine stability of power system [5].
2. Transient stability analysis of power systems with energy storage by Chi Yuan Weng, 2013. This thesis used a DAE (Differential Algebraic Equations) model of SMIB power system transient stability for study the role of ES systems [8].
3. Transient Analysis and Modelling of Multi-machine Systems with Power electronics Controllers for Real-time Application by Kee Han Chan. The propose of thesis is to development a new multi-machine power system model with power electronics controllers for transient analysis in the direct time phase-domain. This model has been used to investigate asymmetrical operation conditions [9].

1.6 Outline and Thesis

Chapter one presents transient stability problem and rotor angle stability, chapter two presents a structure of power system, power system components, power system dynamics and Lyapunov Theory, chapter three reviews the Simulink simulation and simulation using Etap, finally, chapter four presents the conclusion.

CHAPTER 2

FORMULATION OF TRANSIENT STABILITY PROBLEM

2.1 Structure of Power System

In general, a power system consists of three main types of interconnected parts: Generation units, transmission grid, and distribution networks. As shown in Figure 2.1, generation units are connected via the transmission grid to each other and the distribution networks that are represented as loads [10].

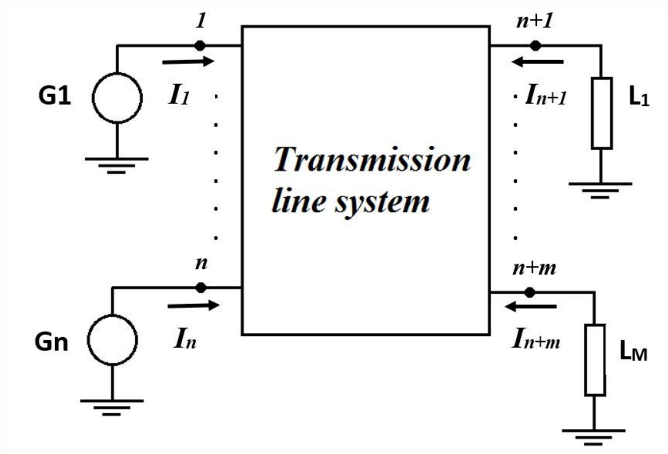

Figure 2-1 Structure of a power system

In normal operation, the system is in a synchronous steady-state, power flowing from the generators to loads. Any disturbance in the structure changes the dynamic interactions among the components of the system. A small change, such as a fault in a transformer of the distribution network, is usually insignificant and the overall effect in the operation of the whole system is negligible. More severe disturbances, such as a fault in the transmission grid, may destroy the integrity of the system, leading to a complete breakdown. The transient stability problem is concerned with analysis of the dynamic behavior of the system under such severe disturbances [11], [12].

2.2 Power System Components

Stability of power system depends upon the equilibrium between output power of generators and consumed power in loads. Therefore, suitable models of each equipment of the system are requirement. In these models, the three-phase system is represented as a single-phase, and the per-unit values are used in computation with MVA base [13].

2.2.1 Generators

The simplest model of a synchronous generator, called the classical model, is described by a second-order swing equation [14] as:

$$M\ddot{\delta} + D\dot{\delta} = P_m - P_e \qquad (2.1)$$

where δ is the electrical rotor angle of the generator relative to a reference frame rotating at a fixed synchronous speed, P_m is the p.u. mechanical power input, P_e is the p.u. electrical power output, and M and D are associated inertia and damping parameters. This simple model neglects the effect of saliency, and assumes constant flux linkages and a constant voltage behind a constant transient impedance. This model is acceptable for the first swing transient stability analysis which has a period of about one second or less [14].

In steady-state, $P_m = P_e$, and the generator is in equilibrium with $\delta = \delta_e$= constant. When a disturbance causes δ to take a different value $\delta_0 \neq \delta_e$, it may or may not return to the equilibrium value as shown in Figure 2.2. If it does, the system maintains its integrity, and it is said to be stable. Otherwise, the generator loses synchronism, and stability is lost.

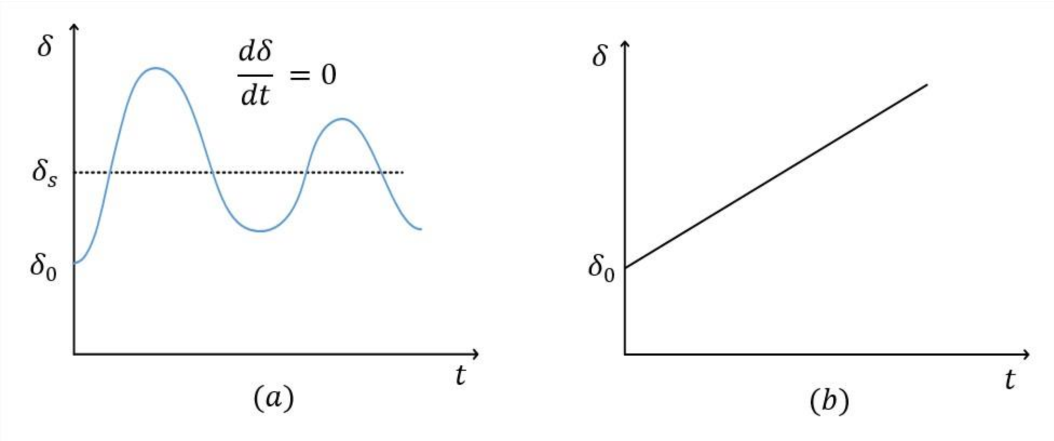

Figure 2-2 Swing curve

In case of the multimachine system of Figure 2.2, each generator G_i is described as:

$$M_i\ddot{\delta}_i + D_i\dot{\delta}_i = P_{mi} - P_{ei} \quad , \quad i = 1,2,\ldots\ldots,n \tag{2.1}$$

where:

$$P_{ei} = \mathcal{R}_e\{\bar{I}_i^{\,*}\bar{V}_i\} \tag{2.2}$$

with $\bar{I}_i$ representing the current injected into the transmission grid by G_i , and $\bar{V}_i$ representing the voltage of node i .

2.2.2 Transmission Network

Referring to the Figure 2.2, let $\bar{I}_G$ and $\bar{I}_L$ denote the vectors of currents injected into the transmission network by the generators and loads, respectively; and let $\bar{V}_G$ and $\bar{V}_L$ denote the vectors of corresponding node voltages, respectively. Then the transmission network is described by:

$$\begin{bmatrix} I_G \\ I_L \end{bmatrix} = \begin{bmatrix} Y_{GG} & Y_{GL} \\ {Y_{GL}}^T & Y_{LL} \end{bmatrix} \begin{bmatrix} V_G \\ V_L \end{bmatrix} \tag{2.3}$$

where the admittances matrices satisfy

$$\bar{Y}_{GG}{}^T = \bar{Y}_{GG} \ , \bar{Y}_{LL}{}^T = \bar{Y}_{LL} \ , \ \bar{Y}_{LG} = \bar{Y}_{GL}{}^T$$

It should be noted that, since the conductances of the transmission lines are negligible compares with their reactances, the admittance matrices in (2.3) have negligible real parts, and can be assumed to be purely imaginary[15].

2.2.3 Loads

In a power system loads change continuously and the generators are controlled accordingly to satisfy the changing demand. However, these changes are very small or very slow compared with the dynamics involves in transient stability analysis. The simplest model for the loads is the constant admittance model.

$$\bar{I}_{Li} = -\bar{Y}_{Li} V_{Li} \quad , \quad i = n+1, \ldots \ldots, m \tag{2.4}$$

which is also termed as static model. A better description termed dynamic model includes possible variations in frequency:

$$D_i \dot{\delta}_i = -P_{li} - P_{ei} \ , \qquad i = n+1, \ldots \ldots, n+m \tag{2.5}$$

where P_{li} is the power demand of load i

Note that the dynamic load model is similar to the generator model in (2.2) with $M_i = 0$ and $P_{mi} = -P_{li}$.

2.3 Power System Dynamics

Equations describing the dynamic of the overall system are obtained by combining (2.2) - (2.4) with (2.5) or (2.6), and are considered separately for static and dynamic load models [16].

2.3.1 Static Loads

Rewriting (2.5) in vector form as:

$$\bar{I}_L = -\bar{Y}_L \bar{V}_L$$

substituting in (2.4), and eliminating $\bar{V}_L$, we obtain:

$$\bar{I}_G = \left[\bar{Y}_{GG} - \bar{Y}_{GL}(\bar{Y}_L + \bar{Y}_{LL})^{-1} \, Y_{GL}{}^T\right]\bar{V}_G = \bar{Y}_{GG,E} \, \bar{V}_G \tag{2.6}$$

Here $\bar{Y}_{GG,E}$ is the equivalent admittance matrix of the transmission network and the loads as seen from generator side. Unlike the admittance matrices in (2.4), $\bar{Y}_{GG,E}$ in (2.6) has a non-negligible real part as illustrated by the following example.

Example 2.1: consider the two-generator, single-load system in Figure 2-3, where X_{ij} are purely reactive transmission line impedances, and X_L is mostly resistive load impedance.

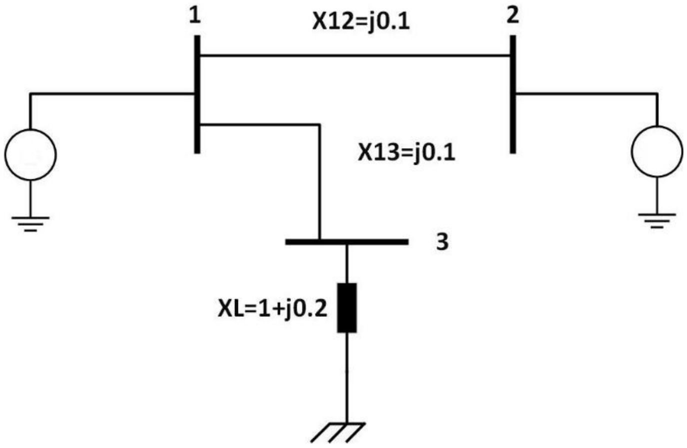

Figure 2-3 A Simple power system

For this simple system, while the transmission network matrix

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \begin{bmatrix} -j20 & j10 & j10 \\ j10 & -j10 & 0 \\ j10 & 0 & -j10 \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix}$$

Is purely imaginary, the equivalent admittance matrix

$$\bar{Y}_{GG,E} \approx \begin{bmatrix} 0.9 - j10.3 & j10 \\ j10 & -j10 \end{bmatrix}$$

has a significant nonzero real part in (1,1) position.

The fact that $\bar{Y}_{GG,E}$ has a nonzero real part creates difficulties in constructing a suitable Lyapunov function for analysis of transient stability [17]. This point will be discussed in Section 2.6.

Let $\bar{I}_i^s$, $\bar{V}_i^s$, $\bar{\delta}_i^s$, $and\ \bar{P}_{ei}^s$, $i = 1,2, \dots \dots, n+m$, denote the stable equilibrium values of the corresponding variables, which are determined by a load-flow analysis [3], [7] of the post-fault system. Clearly, we have

$$
\begin{aligned}
P_{mi} &= P_{ei}^s \qquad , i = 1, \dots, n \\
-P_{li} &= P_{ei}^s \qquad , i = n+1, \dots., m
\end{aligned}
\tag{2.7}
$$

Then, the equation (2.2) and (2.5) describing the dynamics of the generators and the loads take the form [7], [18]

$$
M_i \ddot{\delta}_i + D_i\, \dot{\delta}_i = P_{ei}^s - P_{ei} \qquad , i = 1, \dots, n+m \tag{2.8}
$$

(2.4) in open form is written as

$$
\bar{I}_i = \sum_{j=1}^{n+m} \bar{Y}_{ij}\, \bar{V}_j
$$

$$
= \sum_{j=1}^{n+m} jB_{ij} V_j \left(cos\delta_j + j\ sin\delta_j \right) \ , \quad i = 1, \dots \dots, n+m
$$

so that from (2.3) we have

$$
P_{ei} = \mathcal{R}_e \left\{ \sum_{j=1}^{n+m} -jB_{ij} V_i\, V_j (cos\delta_i + jsin\delta_i)(cos\delta_j - jsin\delta_j) \right\}
$$

$$
= \sum_{j=1}^{n+m} V_i\, V_j\, B_{ij} \left(cos\delta_i sin\delta_j - sin\delta_i cos\delta_j \right)
$$

$$
= - \sum_{j=1}^{n+m} V_i\, V_j\, B_{ij} \sin\left(\delta_i - \delta_j\right) \ , \quad i = 1, \dots, n+m \tag{2.9}
$$

Now, the right-hand side of (2.9) becomes

$$
P_{ei}^s - P_{ei} = - \sum_{j=1}^{n+m} V_i\, V_j\, B_{ij} \left[\sin\left(\delta_i - \delta_j\right) - \sin(\delta_i^s - \delta_j^s) \right] \tag{2.10}
$$

since $B_{ij} = B_{ji}$ it follows that

$$
\sum_i (P_{ei}^s - P_{ei}) = 0
$$

which implies that one of δ_i is redundant in describing the dynamics of the overall system. To eliminate redundancy, we define

$$z_i = (\delta_i - \delta_{n+m}) - (\delta_i^s - \delta_{n+m}^s) , \quad i = 1, \dots , n + m - 1 \qquad (2.11)$$

$$z_{n+m} = 0$$

so that

$$\delta_i - \delta_j = (z_i - z_j) + (\delta_i^s - \delta_j^s) = z_i - z_j + \theta_{ij} \qquad (2.12)$$

We are now ready to construct a state-space model for the overall system: Let $\omega_i = \dot{\delta}_i$, $i = 1, \dots \dots , n + m$. Then from (2.12)

$$\dot{z}_i = \omega_i - \omega_{n+m} , \quad i = 1, \dots , n + m - 1 \qquad (2.13)$$

and from (2.9), (2.11) and (2.13)

$$M_i \dot{\omega}_i + D_i \, \omega_i = - \sum_{j=1}^{n+m} V_i \, V_j \, B_{ij} \left[\sin(z_i - z_j + \theta_{ij}) - \sin \theta_{ij} \right] \qquad (2.14)$$

Finally, let

$$\sigma_{ij} = z_i - z_j \quad , \qquad i = 1, \dots , n + m - 1 \quad , j > i \qquad (2.15)$$

and

$$f_{ij}(\sigma_{ij}) = V_i \, V_j B_{ij} \left[\sin(\sigma_{ij} + \theta_{ij}) - \sin \theta_{ij} \right] \qquad (2.16)$$

Then

$$V_i \, V_j B_{ij} \left[\sin(z_i - z_j + \theta_{ij}) - \sin \theta_{ij} \right] = \begin{cases} f_{ij}(\sigma_{ij}) \ , & j > i \\ -f_{ij}(\sigma_{ij}) \ , & j < i \end{cases} \qquad (2.17)$$

and (2.15) becomes

$$M_i \dot{\omega}_i + D_i \, \omega_i = - \sum_{j>i} f_{ij}(\sigma_{ij}) + \sum_{j<i} f_{ij}(\sigma_{ij}) \qquad (2.18)$$

Example 2.2: To illustrate the construction of the state-space representation of the dynamics, let us consider a $n = 2$ generator, $m = 3$ load system.

z_i in (2.12) are defined as

$$z_i = (\delta_i - \delta_5) - (\delta_i^s - \delta_5^s)\ , i = 1,2,3,4$$
$$z_5 = 0$$

and σ_{ij} in (2.16) as

$$\begin{aligned}
\sigma_{12} &= z_1 - z_2 \\
\sigma_{13} &= z_1 - z_3 \\
\sigma_{14} &= z_1 - z_4 \\
\sigma_{15} &= z_1 - z_5 = z_1 \\
\sigma_{23} &= z_2 - z_3 \\
\sigma_{24} &= z_2 - z_4 \\
\sigma_{25} &= z_2 - z_5 = z_2 \\
\sigma_{34} &= z_3 - z_4 \\
\sigma_{35} &= z_3 - z_5 = z_3 \\
\sigma_{45} &= z_4 - z_5 = z_4
\end{aligned} \tag{2.19}$$

Then (2.14) becomes

$$\begin{aligned}
\dot{z}_1 &= \omega_1 - \omega_5 \\
\dot{z}_2 &= \omega_2 - \omega_5 \\
\dot{z}_3 &= \omega_3 - \omega_5 \\
\dot{z}_4 &= \omega_4 - \omega_5
\end{aligned} \tag{2.20}$$

and (2.15) becomes

$$\begin{aligned}
M_1\dot{\omega}_1 + D_1\ \omega_1 &= -f_{12}(\sigma_{12}) - f_{13}(\sigma_{13}) - f_{14}(\sigma_{14}) - f_{15}(\sigma_{15}) \\
M_2\dot{\omega}_2 + D_2\ \omega_2 &= f_{12}(\sigma_{12}) - f_{23}(\sigma_{23}) - f_{24}(\sigma_{24}) - f_{25}(\sigma_{25}) \\
D_3\ \omega_3 &= f_{13}(\sigma_{13}) + f_{23}(\sigma_{23}) - f_{34}(\sigma_{34}) - f_{35}(\sigma_{35}) \\
D_4\ \omega_4 &= f_{14}(\sigma_{14}) + f_{24}(\sigma_{24}) + f_{34}(\sigma_{34}) - f_{45}(\sigma_{45}) \\
D_5\ \omega_5 &= f_{15}(\sigma_{15}) + f_{25}(\sigma_{25}) + f_{35}(\sigma_{35}) + f_{45}(\sigma_{45})
\end{aligned} \tag{2.21}$$

We now rewrite (2.20) -(2.22) in matrix form: Define

$$\underline{z} = [z_1 \quad z_2 \quad z_3 \quad z_4]^T$$
$$\underline{\omega} = [\omega_1 \quad \omega_2 \quad \omega_3 \quad \omega_4]^T$$
$$\underline{\sigma} = [\sigma_{12} \quad \sigma_{13} \quad \sigma_{14} \quad \sigma_{15} \quad \sigma_{23} \quad \sigma_{24} \quad \sigma_{25} \quad \sigma_{34} \quad \sigma_{35} \quad \sigma_{45}\ ]^T$$

$$\underline{f}(\,\underline{\sigma}\,) = [f_{12}(\sigma_{12}) \ldots \;\; f_{45}(\sigma_{45})]^T$$

Then (2.22) becomes

$$M\underline{\dot{\omega}} + D\underline{\omega} = -F\underline{f}(\,\underline{\sigma}\,) \tag{2.22}$$

(2.21) becomes

$$\underline{\dot{z}} = K\,\underline{\omega} \tag{2.23}$$

and (2.20) becomes

$$\underline{\sigma} = G\,\underline{z} \tag{2.24}$$

where

$$M = diag\{M_1\,, M_2\,, 0\,, 0\,, 0\,\}$$

$$D = diag\{D_1\,, D_2\,, D_3\,, D_4\,, D_5\}$$

$$F = \begin{bmatrix} 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & -1 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & -1 & 0 & 0 & -1 & 0 & -1 & 0 & 1 \\ 0 & 0 & 0 & -1 & 0 & 0 & -1 & 0 & -1 & -1 \end{bmatrix}$$

$$K = \begin{bmatrix} 1 & 0 & 0 & 0 & -1 \\ 0 & 1 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 & -1 \\ 0 & 0 & 0 & 1 & -1 \end{bmatrix}$$

$$G = \begin{bmatrix} 1 & -1 & 0 & 0 \\ 1 & 0 & -1 & 0 \\ 1 & 0 & 0 & -1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 \\ 0 & 1 & 0 & -1 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & -1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Note that

$$GK = F^T \tag{2.25}$$

Note also that if there is no transmission line between nodes $and\ j$, that is, if $B_{ij} = 0$, then $f_{ij}(\sigma_{ij}) = 0$, and there is no need to define the corresponding σ_{ij}. In that case the corresponding row of G and the column of F can be eliminated[19].

Equations (2.23) - (2.25) in Example 2.2 hold for any system with arbitrary number of generators and loads. Since $M_i = 0$ for loads, it is convenient to partition $\underline{\omega}$ as:

$$\underline{\omega} = \begin{bmatrix} \underline{\omega_G} \\ \underline{\omega_L} \end{bmatrix}$$

and the matrices $M\ , D, F\ and\ K$ accordingly as

$$M = \begin{bmatrix} M_G & 0 \\ 0 & 0 \end{bmatrix}, \quad D = \begin{bmatrix} D_G & 0 \\ 0 & D_L \end{bmatrix}, \quad F = \begin{bmatrix} F_G \\ F_L \end{bmatrix}, \quad K = [K_G \quad K_L]$$

and rewrite (2.23) as

$$M\underline{\dot{\omega}}_G + D\underline{\omega}_G = -F_G\underline{f}(\underline{\sigma})$$

$$D_L\underline{\omega}_L = -F_L\underline{f}(\underline{\sigma})$$

and eliminate $\underline{\omega}_L$:

$$\underline{\omega}_L = -D_L^{-1}F_L\underline{f}(\underline{\sigma})$$

Then, a state-space representation is obtained as

$$\begin{bmatrix} \underline{\dot{\omega}}_1 \\ \underline{\dot{z}} \end{bmatrix} = \begin{bmatrix} -M_G^{-1}D_G & 0 \\ K_G & 0 \end{bmatrix} \begin{bmatrix} \underline{\omega}_G \\ \underline{z} \end{bmatrix} - \begin{bmatrix} M_G^{-1}F_G \\ K_L D_L^{-1} F_L \end{bmatrix} \underline{f}(\underline{\sigma}) \tag{2.26}$$

$$\underline{\sigma} = [0 \quad G] \begin{bmatrix} \underline{\omega}_G \\ \underline{z} \end{bmatrix}$$

where, from (2.26) we have

$$GK_G = F_G^T \ , \ GK_L = F_L^T \tag{2.27}$$

2.4 Stability Analysis Using Lyapunov Theory

The state-space model in (2.27) is in the form of the well-known Lur'e-Popov system [2]

$$
\begin{aligned}
\underline{\dot{x}} &= A\underline{x} + B\underline{u} \\
\underline{y} &= C\underline{x} \\
\underline{u} &= -\underline{f}(\underline{y})
\end{aligned}
\tag{2.28}
$$

where

$$
\underline{x} = \begin{bmatrix} \omega_G \\ \underline{z} \end{bmatrix}, \quad \underline{y} = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_N \end{bmatrix} = \begin{bmatrix} \sigma_{12} \\ \sigma_{13} \\ \vdots \\ \sigma_{n+m-1,n+m} \end{bmatrix}
$$

The system is shown in Figure 2.4, where the linear system S is defined by the triple (C, A, B), and the decoupled feedback nonlinearity by $\underline{f}$.

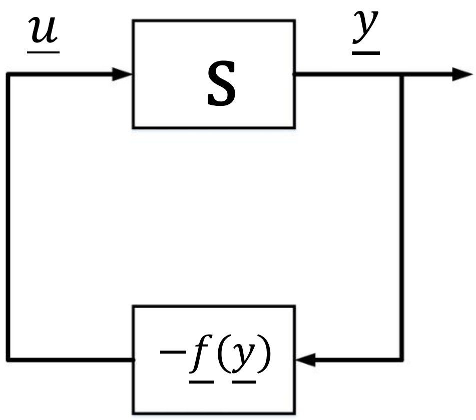

Figure 2-4 Lur'e- Popov system

The components of the feedback nonlinearity

$$
f_p(y_p) = c_p\left[\sin(y_p + \theta_p) - \sin\theta_p\right]
$$

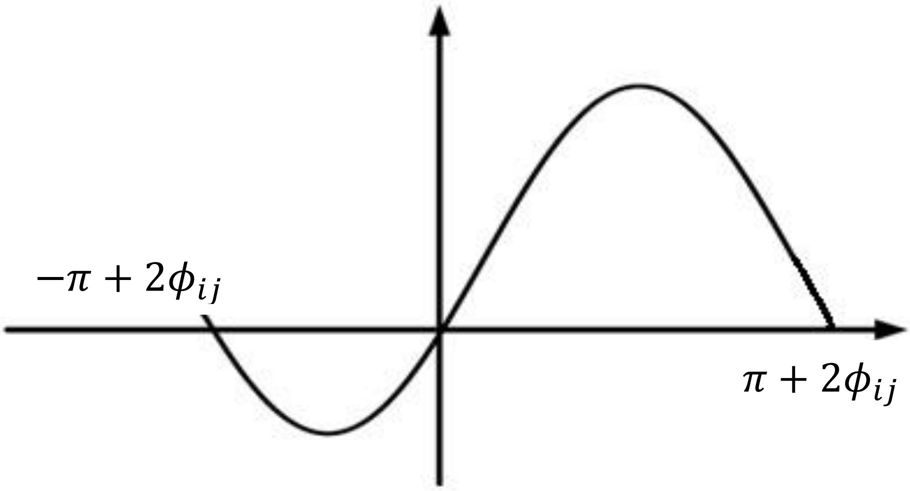

Figure 2-5 Feedback of nonlinearity $f_{ij}(\sigma_{ij})$

where $c_p = V_i V_j B_{ij}$, $\theta_p = \theta_{ij}$, are shown in figure (2.5), and they satisfy

$$0 \leq y_p \, f_p(y_p) \leq \, c_p y_p^2 \quad , \quad -\pi - 2\theta_p \leq y_p \leq \pi - 2\theta_p \qquad (2.29)$$

2.4.1 Moore-Anderson Theorem

Moore-Anderson Theorem [20] provides sufficient conditions for stability of the system described by (2.29) by constructing a Lyapunov function.

Below a result is derived from the Moore-Anderson Theorem whose proof is available in [20].

Theorem 2.1: let $\theta > 0$ satisfy

$$\theta > M_i / D_i \quad , \qquad i = 1, \dots, n$$

Then,

a) The matrix

$$P = \begin{bmatrix} P_{ww} & P_{wz} \\ P_{wz}^T & P_{zz} \end{bmatrix}$$

where

$$P_{zz} = (K \, D^{-1} K^T)^{-1}$$
$$P_{wz} = M_G D_G^{-1} K_G^T P_{zz}$$
$$P_{ww} = \theta M_G + M_G D_G^{-1} (K_G^T P_{zz} K_G - D_G) D_G^{-1} M_G$$

is positive definite

b) The function

$$V(\underline{x}) = \underline{x}^T \underline{P}\, \underline{x} + 2\theta \sum_{i,j} \int_0^{\sigma_{ij}} f_{ij}\,(\zeta)\; d\zeta \tag{2.30}$$

where $\underline{x} = \begin{bmatrix} \underline{\omega}_G^T & \underline{z}^T \end{bmatrix}^T$, is a Lyapunov function for the system (2.27), hence the origin of (2.27) is asymptotically stable.

The Lyapunov function in (2.30) can be used to determine the region of attraction of (2.27) as we explain next.

2.4.2 Region of Attraction

First note that $V(\underline{x}) > 0$ in the region specified in (2.29), that is,

$$\mathcal{R}\colon \sigma_{ij}^m = -\pi - 2\theta_{ij} \le \sigma_{ij} \le \pi - 2\theta_{ij} = \sigma_{ij}^M \tag{2.31}$$

Thus the region of attraction is

$$\mathcal{R}_a = \{\underline{x}\colon V(\underline{x}) \le V_{max}\} \tag{2.32}$$

where

$$V_{max} = \frac{max}{c} \{V(\underline{x}) = c \implies \underline{x} \in \mathcal{R}\} \tag{2.33}$$

It has been shown in [21] that V_{max} is achieved at some $\underline{x}_{max}$ that is on the boundary of $\mathcal{R}$. Thus the problem of finding V_{max} is reduced to a search on the hyperplanes

$$\sigma_{ij} = z_i - z_j = \sigma_{ij}^m \; or \; \sigma_{ij}^M$$

and can easily be programmed to be solved with the help of a computer.

2.5 Remark on Static Load

Derivation of the dynamic model of the power system under the assumption of static loads follows a similar development, except that all the loads are converted into equivalent admittance as illustrated in Example 2.1. Then, (2.9) becomes

$$\begin{aligned} P_{ei} = \mathcal{R}_e &\left\{ \sum_{j=1}^{n} (G_{ij} - jB_{ij}) V_i V_j \big(\cos\delta_i + j\sin\delta_i\big)\big(\cos\delta_j - \mathrm{j}\sin\delta_j\big) \right\} \\ &= -\sum_{j=1}^{n} V_i V_j Y_{ij} \sin\big(\delta_i - \delta_i + \phi_{ij}\big), \qquad i = 1, \dots, n \end{aligned} \tag{2.34}$$

where

$$Y_{ij} = \left(G_{ij}^2 + B_{ij}^2\right)^{1/2}, \phi_{ij} = \tan^{-1}\big(G_{ij}/B_{ij}\big)$$

and accordingly (2.14) becomes

$$M_i \dot{\omega}_i + D_i\, \omega_i = -\sum_{j=1}^{n} V_i\, V_j\, Y_{ij} \left[\sin\big(z_i - z_j + \theta_{ij}\big) - \sin\theta_{ij}\right] \tag{2.35}$$

where

$$\theta_{ij} = \delta_i^s - \delta_j^s + \phi_{ij} \tag{2.36}$$

Now, unlike the case of dynamic loads, $\theta_{ij} \neq -\theta_{ji}$ because $\phi_{ij} = \phi_{ji}$. This breaks the symmetry leading to (2.18), and makes construction of a suitable Lyapunov function as in Theorem 2.1 impossible.

CHAPTER 3

AN EXAMPLE SYSTEM

To illustrate the use of Lyapunov theory in transient stability analysis of a power system [17], we consider the structure in Figure 3.1

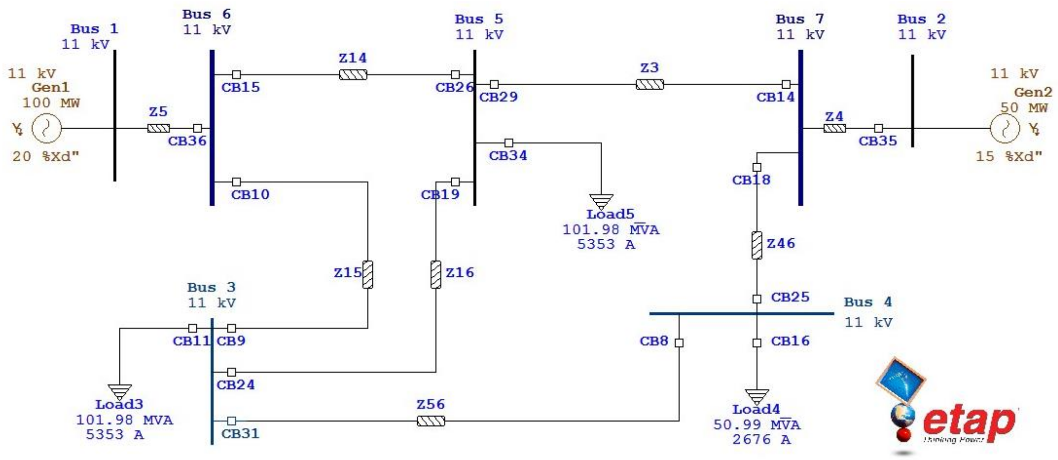

Figure 3-1 An example system

3.1 System Data

Generator Ratings:

	KV	MVA	MW	X''_d %	$P.F$ %	Eff.%	M%	D %
G_1	11	125	100	20	80	97.41	50	20
G_2	11	62.5	50	10	80	97.41	40	10

Load Ratings:

	KV	MVA	MW	$MVar$	$P.F$ %	$Amps.$	M%	D %
$_3$	11	101.98	100	20	98.06	5353	0	25
L_4	11	50.99	50	10	98.06	2676	0	25
L_5	11	101.98	100	20	98.06	5353	0	20

Transmission Line Impedances:

TL_{16}	$j0.050$
TL_{27}	$j0.030$
TL_{34}	$j0.175$
TL_{35}	$j0.215$
TL_{36}	$j0.105$
TL_{47}	$j0.125$
TL_{56}	$j0.225$
TL_{57}	$j0.040$

Fault Description:

A 3-phase short circuit occurs at the mid-point of TL_{57}, which is cleared by opening circuit breakers 14 and 29 at both ends of the line.

3.2 Simulation Using Etap

Etap is a powerful software that can be used for power system simulations [22], in particular, for load-flow analysis and for dynamic response.

Results of the simulation of the dynamic behavior of the system under stated fault and clearing conditions are given in Appendix A for a fault that occurred at $t_f = 0.2$ sec. and cleared at $t_{c1} = 1$ sec. and $t_{c2} = 0.6$ sec.

The load angles δ_1 and δ_2 of the generators and δ_3, δ_4 and δ_5 of the loads are shown in Figures 3.2 and Figure 3.3 for both clearing times.

It is observed that the system remains stable for the shorter clearing time $t_{c2} = 0.6$ sec., but loses synchronism for $t_{c1} = 1.0$ sec.

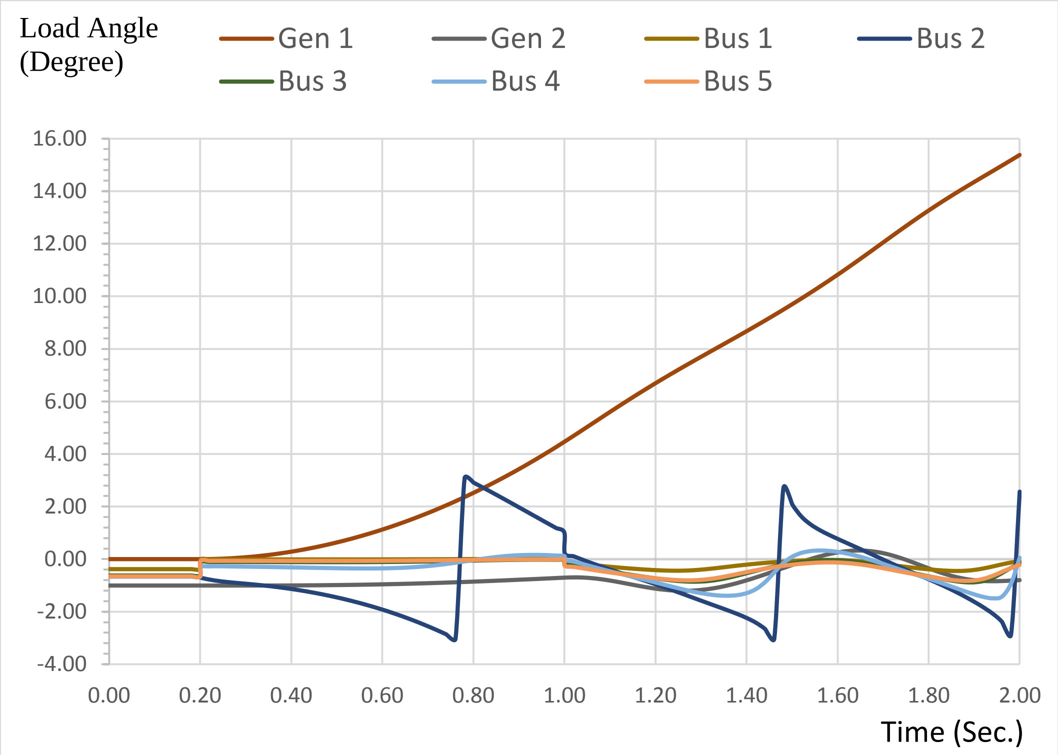

Figure 3-2 Load angles for $t_{c1} = 1.0$ sec.

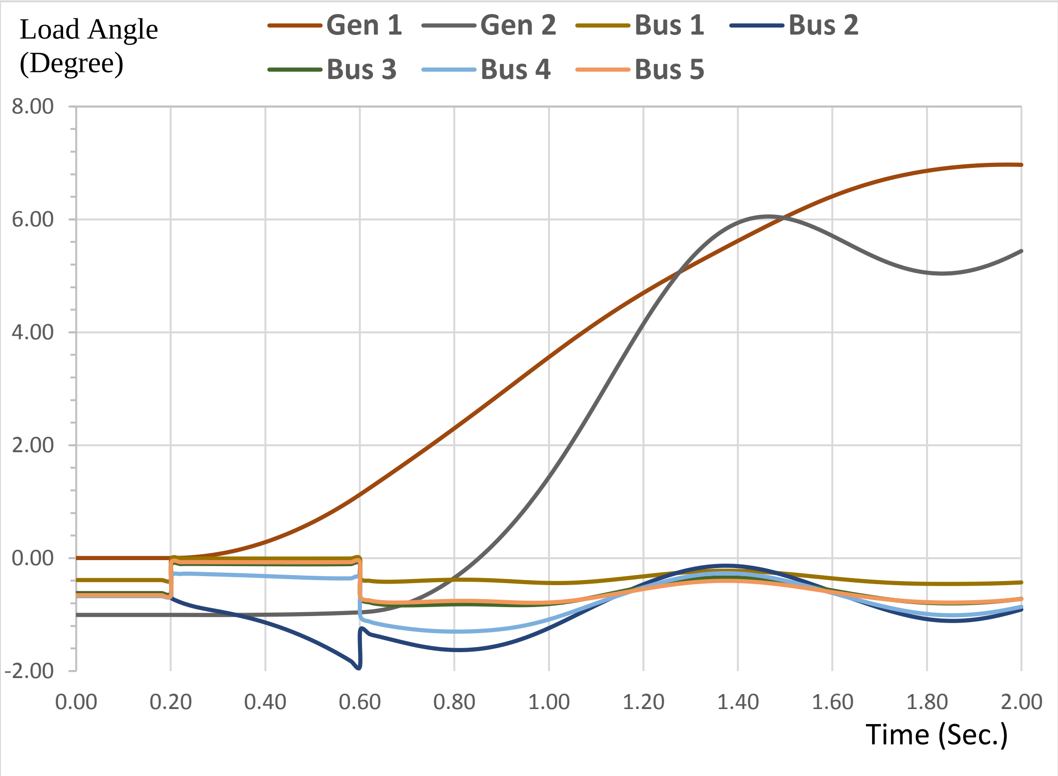

Figure 3-3 Load angles for t_{c2}=0.6 sec.

3.3 Simulink Model of the Post-fault System

The Simulink [23] model of (2.27) for the example system is shown in Figure 3.4.

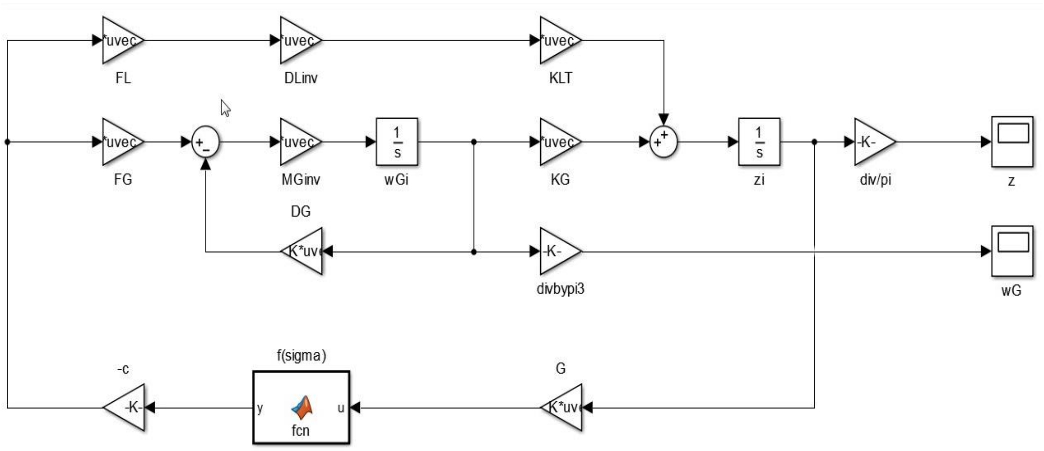

Figure 3-4 Simulink model

The admittance matrix of the post-fault system is calculated, by eliminating the internal nodes 6 and 7, to be

$$\overline{Y} = j\begin{bmatrix} -j8.2243 & 0 & j5.6075 & 0 & j2.6168 \\ 0 & -j6.4516 & 0 & j6.4516 & 0 \\ j5.6075 & 0 & -j17.2190 & j5.7143 & j5.8973 \\ 0 & j6.4516 & -j5.71430 & -j12.1659 & 0 \\ j2.6168 & 0 & j5.8973 & 0 & -j8.5141 \end{bmatrix} \tag{3.1}$$

Since $B_{12} = B_{14} = B_{23} = B_{25} = B_{45} = 0$, there is no need to define corresponding σ_{ij}. Therefore,

$$\underline{\sigma} = \begin{bmatrix} \sigma_{13} \\ \sigma_{15} \\ \sigma_{24} \\ \sigma_{34} \\ \sigma_{35} \end{bmatrix} = \begin{bmatrix} 1 & 0 & -1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & -1 \\ 0 & 0 & 1 & -1 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \end{bmatrix} = G\underline{z} \tag{3.2}$$

$$\underline{\dot{z}} = \begin{bmatrix} \omega_1 - \omega_5 \\ \omega_2 - \omega_5 \\ \omega_3 - \omega_5 \\ \omega_4 - \omega_5 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & -1 \\ 0 & 1 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 & -1 \\ 0 & 0 & 0 & 1 & -1 \end{bmatrix} \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \\ \omega_4 \end{bmatrix} = K\underline{\omega} \tag{3.3}$$

And hence

$$F = (GK)^T = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ \hline -1 & 0 & 0 & 1 & 1 \\ 0 & 0 & -1 & -1 & 0 \\ 0 & -1 & 0 & 0 & -1 \end{bmatrix} \qquad (3.4)$$

where K_G , K_L , F_G and F_L are indicated in (3.3) and (3.4).

Remaining parameters of the linear part of the system are readily constructed from the generator and load data as

$$M_G = \begin{bmatrix} 0.5 & 0 \\ 0 & 0.4 \end{bmatrix} , \quad D_G = \begin{bmatrix} 0.2 & 0 \\ 0 & 0.1 \end{bmatrix} , \quad D_L = \begin{bmatrix} 0.25 & 0 & 0 \\ 0 & 0.25 & 0 \\ 0 & 0 & 0.2 \end{bmatrix} \qquad (3.5)$$

Finally, to determine the parameters of the feedback nonlinearity, we need V_i , V_j and θ_{ij} of the post-fault equilibrium. For this, we perform a load-flow analysis of the post-fault system using Etap, whose results are shown in Figure 3.5.

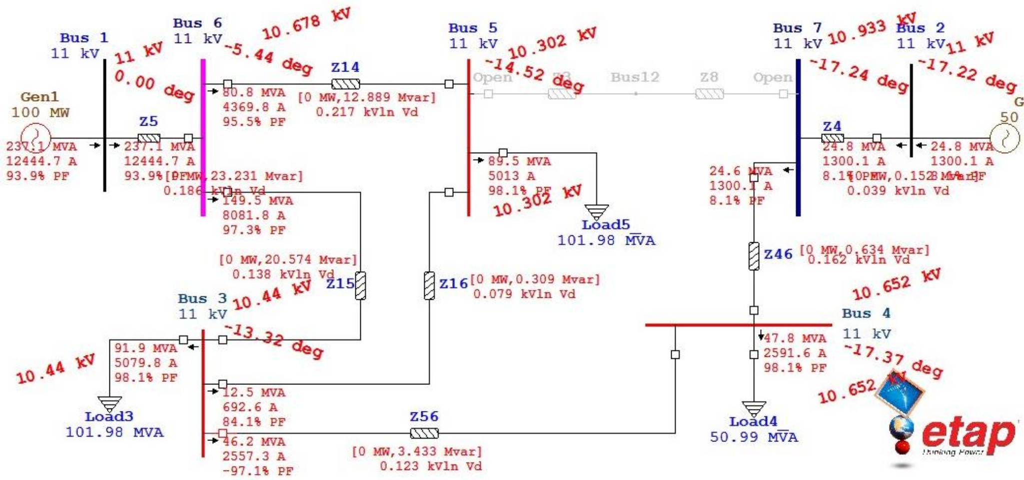

Figure 3-5 Load-Flow results of post-fault system

From the load-flow analysis, we determine

$$\underline{V}^s = [1.0000 \quad 1.0000 \quad 0,9491 \quad 0,9684 \quad 0,9365]^T \qquad (3.6)$$

$$\underline{\delta}^s = [0.000 \quad -17.22 \quad -13.32 \quad -17.37 \quad -14.52]^T$$

where V_i are in $p.u.$ and δ_i^s are in degrees. Converting load angles into radians, and using the admittance values in (3.1) we calculate

$$\underline{c} = [5{,}3220 \quad 2{,}4508 \quad 6{,}2475 \quad 5{,}2518 \quad 5{,}2419]^T$$
$$\underline{\theta} = [0.2325 \quad 0.2534 \quad 0.0026 \quad 0.0707 \quad 0.0209]^T$$

3.4 Simulation of the Simulink Model

The model in Figure 3.4 is simulated for two sets of initial conditions corresponding to $t_{c1} = 1$ sec. and $t_{c2} = 0.6$ sec., which are taken from Etap simulations of the fault given in Appendix A, the $\underline{\omega}_G$ and $\underline{z}$ values at a $t_{c1} = 1.0$ sec. are read as

$$\begin{aligned} \underline{\omega}_{G1} &= [-0.0421 \quad -9.6421]^T \\ \underline{z}_1 &= [0.0300 \quad 1.0246 \quad -0.0028 \quad 0.1335]^T \end{aligned} \tag{3.7}$$

Simulation results of the post-fault system corresponding to these initial condition are shown in Figure 3.6. It is observed that the system is unstable, confirming the result obtained from Etap simulation.

The $\underline{\omega}_G$ and $\underline{z}_1$ values at $t_{c2} = 0.6$ sec. are read from table 4 in Appendix A

$$\underline{\omega}_{G2} = [0.0211 \quad -5.2782]^T$$
$$\underline{z}_2 = [0.0613 \quad -1.8561 \quad -0.0377 \quad -0.2851]^T$$

Simulation results of the post-fault system corresponding to these initial condition are shown in Figure 3.7. It is observed that the system is stable, confirming the result obtained from Etap simulation.

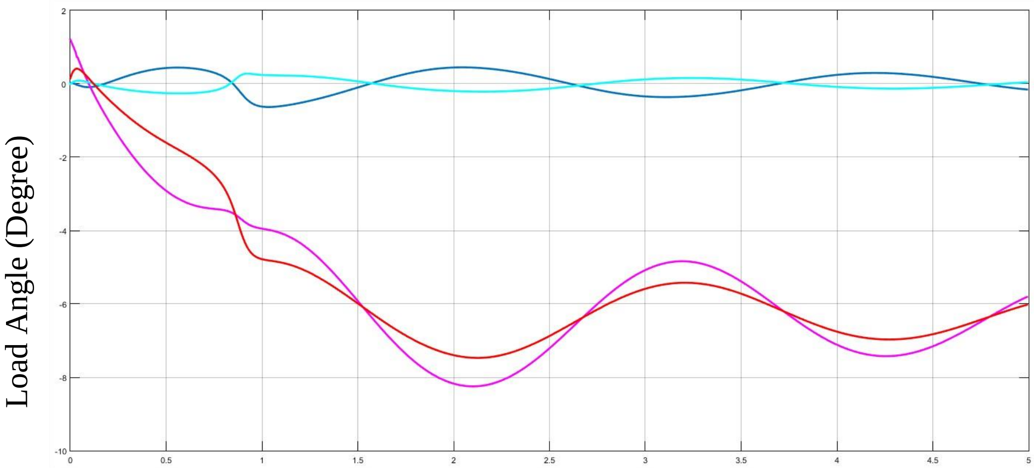

Figure 3-6 Simulating result $t_{c1} = 1$ sec.

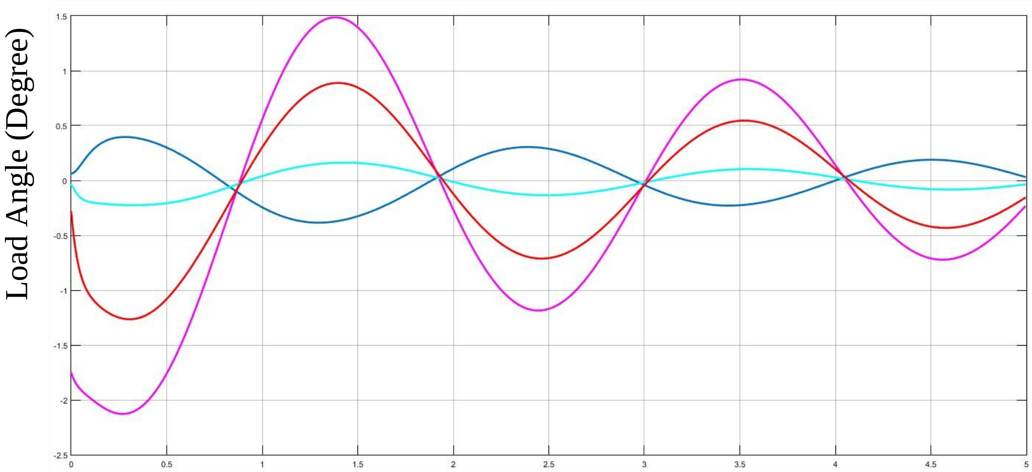

Figure 3-7 Simulating result $t_{c2} = 0.6$ sec.

3.5 Calculation and Verification of the Region of Attraction

In this section we first calculate the region of attraction given in (2.33), and then verify it using simulation results.

The blocks of the matrix P in theorem 2.1 are calculated as

$$P_{\omega\omega} = \begin{bmatrix} 2.0000 & -0.4000 \\ -0.40000 & 1.9800 \end{bmatrix}$$

$$P_{\omega z} = \begin{bmatrix} 0.3000 & -0.1000 & -0.1000 & -0.0500 \\ -0.1600 & 0.3200 & -0.0800 & -0.0400 \end{bmatrix}$$

$$P_{zz} = \begin{bmatrix} 0.1200 & -0.0400 & -0.0400 & -0.0200 \\ -0.0400 & 0.0800 & -0.0200 & -0.0100 \\ -0.0400 & -0.0200 & 0.0800 & -0.0100 \\ -0.0200 & -0.0100 & -0.0100 & 0.0450 \end{bmatrix}$$

V_{max} in (2.3) occurs at

$$\underline{z}_{max} = 0.01 * [-0.1047 \quad -299.7079 \quad 0.2094 \quad -299.8127]$$

Corresponding to

$$\underline{S}_{max} = 0.01 * [-0.3152 \quad -0.1057 \quad 0.1057 \quad 300.0221]$$

And

$$\underline{\omega}_{G\,max} = -P_{\omega\omega}^{-1} \; P_{\omega Z} \; \underline{z}_{max} = [-0.1309 \quad 0.4683]$$

The value of V_{max} is then evaluated as

$$V_{max} = 113.8033$$

The value of $V(\,\underline{x}\,)$ corresponding to the initial condition in (3.7) is calculated as

$$V_1 = 157.4832$$

Since $V_1 > V_{max}$, the initial condition is outside the region of attraction, and we can say nothing about the stability of the system. In fact, the system is unstable as indicated by both Etap and Simulink simulations.

On the other hand, the value of $V(\underline{x})$ corresponding to the initial condition in (3.8) is calculated as

$$V_2 = 73.7622$$

And $V_2 < V_1$. Thus, the initial condition is within the region of attraction and we expect the solution to reach a steady-state. This is indeed the case as observed from Etap and Simulink simulation.

CHAPTER 4

CONCLUSION

4.1 Stability by Comparison

In spite of small gap between the critical clearing time obtained by simulation and Lyapunov's method, the result of structure preserving energy using Lyapunov's direct method are the same as the result of ETAP. Structure preserving models are open a new area of research for power system stability.

4.2 Inference

1. The clearing time of the protection circuit in power system in the major interesting stability of power system.
2. The model as represented in equation (2.26) is known as structure preserving model simply because a changing in the parameter in transmission line effects only on $f_i(\sigma_i)$, but not for A, B, C and D parameters.

4.3 Problem in Lyapunov Direct Method

1. Lyapunov's direct method is unlikely because it not requires more details models of generating unit like capability, dynamic model in (sub-transient, transient and equivalent), details of the inertia calculation, exciter, governor, ..etc.)
2. In dynamic system, when the load frequency coefficient (D) are close to zero that will make the load angle too large near of infinity value, in that case ω will become zero. So that the behaviour of the system like a static load.
3. P matrix in Lyapunov direct method, has been changing whenever the (D) parameter of load changed. P and D has an inverse relation.
4. The elements of state matrix refer to A, B, C and D dependent on the system parameters M_i.

From the above, it is clear that the power system needs an alternative method to solve the TSP. The solution of transient stability is not solve just by clearing time, but it should be reduce the number of simulations for each problem. Another issue, power system are not usually have a constant generation and consumption of power during daily load curve. In that case, the best solution is on-line method that deals with system operation on a real-time.

4.4 Future Work

The estimation stability of power system needs essentially important issues that will give result near to the fact, first: online update data which measure the exact value of power system, second: TSA which is greatly important in actual operation of power system to estimate [24].

For future work, the proposed method can be improved by using a better searching method of severely disturbed machines. Also, the method can be tested for a different post-fault configuration which may require some optimization techniques since the post-fault trajectories are unknown.

This thesis concentrate on a direct method of Lyapunov to find the stability of the system which is introduced and several widely used direct methods are investigated.

A better program may improve the fault analysis and stability such as Etap, which is still being investigated in future work practically. This software may improve the optimization techniques in power system stability.

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APPENDIX

APPENDIX A

Table A.1 Etap Results for $t_{c1} = 1\ sec.$ (Measured)

Time (sec.)	δ_1	δ_2	δ_3	δ_4	δ_5
0.0000	-0.3861	-0.6584	-0.6195	-0.6727	-0.6552
0.0200	-0.3861	-0.6584	-0.6195	-0.6727	-0.6552
0.0400	-0.3861	-0.6584	-0.6195	-0.6727	-0.6552
0.0600	-0.3861	-0.6584	-0.6195	-0.6727	-0.6552
0.0800	-0.3861	-0.6584	-0.6195	-0.6727	-0.6552
0.1000	-0.3861	-0.6584	-0.6195	-0.6727	-0.6552
0.1200	-0.3861	-0.6584	-0.6195	-0.6727	-0.6552
0.1400	-0.3861	-0.6584	-0.6195	-0.6727	-0.6552
0.1600	-0.3861	-0.6584	-0.6195	-0.6727	-0.6552
0.1800	-0.3861	-0.6584	-0.6195	-0.6727	-0.6552
0.2000	-0.3861	-0.6584	-0.6195	-0.6727	-0.6552
0.2010	-0.0112	-0.7085	-0.1199	-0.3113	-0.0789
0.2210	-0.0079	-0.7845	-0.1065	-0.2778	-0.0701
0.2410	-0.0073	-0.8383	-0.1042	-0.2740	-0.0686
0.2610	-0.0073	-0.8785	-0.1045	-0.2782	-0.0687
0.2810	-0.0074	-0.9115	-0.1052	-0.2833	-0.0691
0.3010	-0.0075	-0.9426	-0.1059	-0.2882	-0.0694
0.3210	-0.0076	-0.9749	-0.1066	-0.2932	-0.0698
0.3410	-0.0077	-1.0102	-0.1073	-0.2985	-0.0701
0.3610	-0.0078	-1.0496	-0.1080	-0.3042	-0.0705
0.3810	-0.0079	-1.0935	-0.1087	-0.3103	-0.0709
0.4010	-0.0080	-1.1422	-0.1094	-0.3167	-0.0712
0.4210	-0.0081	-1.1959	-0.1101	-0.3234	-0.0715
0.4410	-0.0081	-1.2548	-0.1106	-0.3301	-0.0717
0.4610	-0.0082	-1.3190	-0.1111	-0.3367	-0.0719
0.4810	-0.0081	-1.3887	-0.1113	-0.3429	-0.0719
0.5010	-0.0080	-1.4638	-0.1113	-0.3484	-0.0718
0.5210	-0.0079	-1.5447	-0.1110	-0.3530	-0.0715
0.5410	-0.0077	-1.6315	-0.1103	-0.3562	-0.0709
0.5610	-0.0073	-1.7244	-0.1092	-0.3575	-0.0701
0.5810	-0.0069	-1.8236	-0.1075	-0.3565	-0.0691
0.6010	-0.0064	-1.9294	-0.1054	-0.3526	-0.0677
0.6210	-0.0058	-2.0419	-0.1026	-0.3451	-0.0660
0.6410	-0.0051	-2.1615	-0.0992	-0.3332	-0.0639
0.6610	-0.0042	-2.2883	-0.0952	-0.3162	-0.0614

0.6810	-0.0032	-2.4226	-0.0904	-0.2934	-0.0586
0.7010	-0.0021	-2.5644	-0.0850	-0.2643	-0.0554
0.7210	-0.0010	-2.7137	-0.0789	-0.2286	-0.0519
0.7410	0.0002	-2.8705	-0.0724	-0.1866	-0.0480
0.7610	0.0016	-3.0344	-0.0653	-0.1392	-0.0440
0.7810	0.0029	3.0781	-0.0580	-0.0883	-0.0399
0.8010	0.0043	2.9015	-0.0507	-0.0363	-0.0357
0.8210	0.0056	2.7197	-0.0435	0.0139	-0.0316
0.8410	0.0069	2.5336	-0.0367	0.0595	-0.0278
0.8610	0.0080	2.3443	-0.0305	0.0981	-0.0243
0.8810	0.0090	2.1528	-0.0253	0.1280	-0.0214
0.9010	0.0097	1.9600	-0.0212	0.1482	-0.0191
0.9210	0.0101	1.7667	-0.0186	0.1585	-0.0176
0.9410	0.0103	1.5732	-0.0174	0.1592	-0.0171
0.9610	0.0101	1.3799	-0.0180	0.1509	-0.0175
0.9810	0.0096	1.1869	-0.0203	0.1345	-0.0189
1.0000	0.0088	1.0037	-0.0240	0.1123	-0.0212
1.0010	-0.1208	0.2168	-0.1899	-0.0277	-0.2615
1.0210	-0.1504	0.0984	-0.2329	-0.0980	-0.3008
1.0410	-0.1879	-0.0349	-0.2928	-0.1923	-0.3538
1.0610	-0.2256	-0.1637	-0.3542	-0.2875	-0.4079
1.0810	-0.2616	-0.2865	-0.4142	-0.3799	-0.4605
1.1010	-0.2953	-0.4039	-0.4721	-0.4691	-0.5109
1.1210	-0.3265	-0.5170	-0.5274	-0.5555	-0.5587
1.1410	-0.3553	-0.6274	-0.5807	-0.6399	-0.6043
1.1610	-0.3816	-0.7374	-0.6324	-0.7239	-0.6480
1.1810	-0.4052	-0.8493	-0.6829	-0.8089	-0.6898
1.2010	-0.4252	-0.9650	-0.7316	-0.8958	-0.7290
1.2210	-0.4398	-1.0851	-0.7768	-0.9842	-0.7635
1.2410	-0.4466	-1.2091	-0.8152	-1.0722	-0.7903
1.2610	-0.4436	-1.3356	-0.8429	-1.1571	-0.8056
1.2810	-0.4295	-1.4629	-0.8555	-1.2355	-0.8057
1.3010	-0.4046	-1.5897	-0.8491	-1.3035	-0.7880
1.3210	-0.3707	-1.7155	-0.8209	-1.3569	-0.7519
1.3410	-0.3312	-1.8407	-0.7707	-1.3909	-0.6993
1.3610	-0.2895	-1.9676	-0.7014	-1.3995	-0.6348
1.3810	-0.2485	-2.1007	-0.6186	-1.3733	-0.5642
1.4010	-0.2103	-2.2485	-0.5293	-1.2968	-0.4930
1.4210	-0.1756	-2.4268	-0.4400	-1.1431	-0.4250
1.4410	-0.1447	-2.6668	-0.3555	-0.8781	-0.3627
1.4610	-0.1173	-3.0314	-0.2787	-0.5100	-0.3068
1.4810	-0.0933	2.6904	-0.2108	-0.1521	-0.2576
1.5010	-0.0724	2.0624	-0.1526	0.0959	-0.2152
1.5210	-0.0548	1.6085	-0.1047	0.2374	-0.1799
1.5410	-0.0412	1.3131	-0.0683	0.3065	-0.1528

1.5610	-0.0325	1.0984	-0.0447	0.3272	-0.1350
1.5810	-0.0299	0.9208	-0.0354	0.3134	-0.1283
1.6010	-0.0349	0.7593	-0.0416	0.2728	-0.1341
1.6210	-0.0485	0.6034	-0.0640	0.2101	-0.1535
1.6410	-0.0714	0.4477	-0.1022	0.1291	-0.1866
1.6610	-0.1032	0.2902	-0.1545	0.0333	-0.2323
1.6810	-0.1424	0.1309	-0.2183	-0.0735	-0.2883
1.7010	-0.1866	-0.0287	-0.2900	-0.1876	-0.3515
1.7210	-0.2328	-0.1867	-0.3657	-0.3046	-0.4181
1.7410	-0.2782	-0.3405	-0.4416	-0.4211	-0.4846
1.7610	-0.3207	-0.4893	-0.5154	-0.5349	-0.5487
1.7810	-0.3595	-0.6343	-0.5863	-0.6464	-0.6096
1.8010	-0.3944	-0.7798	-0.6553	-0.7580	-0.6679
1.8210	-0.4246	-0.9305	-0.7227	-0.8729	-0.7232
1.8410	-0.4471	-1.0904	-0.7864	-0.9924	-0.7729
1.8610	-0.4568	-1.2611	-0.8410	-1.1154	-0.8110
1.8810	-0.4476	-1.4429	-0.8764	-1.2375	-0.8277
1.9010	-0.4145	-1.6367	-0.8783	-1.3518	-0.8105
1.9210	-0.3571	-1.8462	-0.8283	-1.4467	-0.7472
1.9410	-0.2821	-2.0844	-0.7102	-1.4983	-0.6339
1.9610	-0.2018	-2.3886	-0.5282	-1.4345	-0.4859
1.9810	-0.1289	-2.8741	-0.3261	-0.9337	-0.3373
2.0000	-0.0746	2.5637	-0.1681	0.0498	-0.2243

Table A.2 Etap Results for $t_{c2} = 0.6\ sec$. (Measured)

Time (sec.)	δ_1	δ_2	δ_3	δ_4	δ_5
0.0000	-0.3861	-0.6584	-0.6195	-0.6727	-0.6552
0.0200	-0.3861	-0.6584	-0.6195	-0.6727	-0.6552
0.0400	-0.3861	-0.6584	-0.6195	-0.6727	-0.6552
0.0600	-0.3861	-0.6584	-0.6195	-0.6727	-0.6552
0.0800	-0.3861	-0.6584	-0.6195	-0.6727	-0.6552
0.1000	-0.3861	-0.6584	-0.6195	-0.6727	-0.6552
0.1200	-0.3861	-0.6584	-0.6195	-0.6727	-0.6552
0.1400	-0.3861	-0.6584	-0.6195	-0.6727	-0.6552
0.1600	-0.3861	-0.6584	-0.6195	-0.6727	-0.6552
0.1800	-0.3861	-0.6584	-0.6195	-0.6727	-0.6552
0.2000	-0.3861	-0.6584	-0.6195	-0.6727	-0.6552
0.2010	-0.0112	-0.7085	-0.1199	-0.3113	-0.0789
0.2210	-0.0079	-0.7845	-0.1065	-0.2778	-0.0701
0.2410	-0.0073	-0.8383	-0.1042	-0.2740	-0.0686
0.2610	-0.0073	-0.8785	-0.1045	-0.2782	-0.0687
0.2810	-0.0074	-0.9115	-0.1052	-0.2833	-0.0691
0.3010	-0.0075	-0.9426	-0.1059	-0.2882	-0.0694
0.3210	-0.0076	-0.9749	-0.1066	-0.2932	-0.0698
0.3410	-0.0077	-1.0102	-0.1073	-0.2985	-0.0701
0.3610	-0.0078	-1.0496	-0.1080	-0.3042	-0.0705
0.3810	-0.0079	-1.0935	-0.1087	-0.3103	-0.0709
0.4010	-0.0080	-1.1422	-0.1094	-0.3167	-0.0712
0.4210	-0.0081	-1.1959	-0.1101	-0.3234	-0.0715
0.4410	-0.0081	-1.2548	-0.1106	-0.3301	-0.0717
0.4610	-0.0082	-1.3190	-0.1111	-0.3367	-0.0719
0.4810	-0.0081	-1.3887	-0.1113	-0.3429	-0.0719
0.5010	-0.0080	-1.4638	-0.1113	-0.3484	-0.0718
0.5210	-0.0079	-1.5447	-0.1110	-0.3530	-0.0715
0.5410	-0.0077	-1.6315	-0.1103	-0.3562	-0.0709
0.5610	-0.0073	-1.7244	-0.1092	-0.3575	-0.0701
0.5810	-0.0069	-1.8236	-0.1075	-0.3565	-0.0691
0.6000	-0.0065	-1.9239	-0.1055	-0.3529	-0.0678
0.6010	-0.3538	-1.2713	-0.7013	-1.0247	-0.6750
0.6210	-0.3990	-1.3464	-0.7834	-1.1236	-0.7470
0.6410	-0.4140	-1.3893	-0.8149	-1.1680	-0.7734
0.6610	-0.4169	-1.4302	-0.8288	-1.1996	-0.7832
0.6810	-0.4141	-1.4714	-0.8346	-1.2262	-0.7850
0.7010	-0.4083	-1.5110	-0.8354	-1.2489	-0.7823
0.7210	-0.4014	-1.5471	-0.8331	-1.2675	-0.7770
0.7410	-0.3943	-1.5778	-0.8290	-1.2820	-0.7706
0.7610	-0.3881	-1.6018	-0.8242	-1.2922	-0.7642

0.7810	-0.3833	-1.6182	-0.8199	-1.2983	-0.7590
0.8010	-0.3805	-1.6263	-0.8169	-1.3007	-0.7556
0.8210	-0.3800	-1.6258	-0.8157	-1.2995	-0.7546
0.8410	-0.3817	-1.6163	-0.8166	-1.2947	-0.7562
0.8610	-0.3858	-1.5979	-0.8193	-1.2862	-0.7601
0.8810	-0.3920	-1.5705	-0.8232	-1.2736	-0.7660
0.9010	-0.3999	-1.5342	-0.8275	-1.2562	-0.7729
0.9210	-0.4088	-1.4894	-0.8309	-1.2336	-0.7799
0.9410	-0.4181	-1.4365	-0.8321	-1.2053	-0.7857
0.9610	-0.4267	-1.3760	-0.8299	-1.1708	-0.7890
0.9810	-0.4337	-1.3088	-0.8231	-1.1303	-0.7886
1.0010	-0.4380	-1.2358	-0.8111	-1.0839	-0.7836
1.0210	-0.4391	-1.1582	-0.7936	-1.0324	-0.7735
1.0410	-0.4363	-1.0775	-0.7710	-0.9768	-0.7583
1.0610	-0.4298	-0.9951	-0.7438	-0.9183	-0.7386
1.0810	-0.4197	-0.9125	-0.7132	-0.8582	-0.7151
1.1010	-0.4068	-0.8308	-0.6801	-0.7978	-0.6888
1.1210	-0.3917	-0.7511	-0.6457	-0.7380	-0.6607
1.1410	-0.3751	-0.6740	-0.6108	-0.6795	-0.6317
1.1610	-0.3574	-0.5999	-0.5761	-0.6230	-0.6024
1.1810	-0.3393	-0.5290	-0.5419	-0.5685	-0.5733
1.2010	-0.3211	-0.4615	-0.5088	-0.5166	-0.5448
1.2210	-0.3032	-0.3981	-0.4771	-0.4676	-0.5174
1.2410	-0.2860	-0.3393	-0.4475	-0.4222	-0.4916
1.2610	-0.2701	-0.2861	-0.4206	-0.3812	-0.4681
1.2810	-0.2559	-0.2395	-0.3969	-0.3453	-0.4473
1.3010	-0.2439	-0.2005	-0.3771	-0.3154	-0.4299
1.3210	-0.2344	-0.1700	-0.3616	-0.2920	-0.4162
1.3410	-0.2277	-0.1487	-0.3508	-0.2757	-0.4067
1.3610	-0.2240	-0.1370	-0.3449	-0.2669	-0.4014
1.3810	-0.2232	-0.1352	-0.3438	-0.2655	-0.4005
1.4010	-0.2255	-0.1431	-0.3477	-0.2715	-0.4038
1.4210	-0.2307	-0.1605	-0.3564	-0.2848	-0.4114
1.4410	-0.2386	-0.1867	-0.3695	-0.3048	-0.4229
1.4610	-0.2490	-0.2210	-0.3867	-0.3310	-0.4380
1.4810	-0.2615	-0.2623	-0.4075	-0.3627	-0.4563
1.5010	-0.2757	-0.3096	-0.4314	-0.3990	-0.4772
1.5210	-0.2912	-0.3615	-0.4577	-0.4390	-0.5002
1.5410	-0.3076	-0.4169	-0.4857	-0.4818	-0.5246
1.5610	-0.3242	-0.4747	-0.5149	-0.5266	-0.5500
1.5810	-0.3409	-0.5339	-0.5446	-0.5724	-0.5756
1.6010	-0.3572	-0.5938	-0.5744	-0.6188	-0.6012
1.6210	-0.3729	-0.6536	-0.6038	-0.6651	-0.6264
1.6410	-0.3877	-0.7129	-0.6325	-0.7110	-0.6507
1.6610	-0.4014	-0.7710	-0.6601	-0.7558	-0.6739

1.6810	-0.4137	-0.8273	-0.6862	-0.7991	-0.6956
1.7010	-0.4245	-0.8812	-0.7105	-0.8403	-0.7155
1.7210	-0.4336	-0.9316	-0.7324	-0.8787	-0.7332
1.7410	-0.4409	-0.9777	-0.7516	-0.9134	-0.7484
1.7610	-0.4465	-1.0184	-0.7678	-0.9438	-0.7610
1.7810	-0.4504	-1.0528	-0.7807	-0.9692	-0.7709
1.8010	-0.4530	-1.0799	-0.7904	-0.9890	-0.7781
1.8210	-0.4544	-1.0989	-0.7968	-1.0028	-0.7827
1.8410	-0.4548	-1.1094	-0.7999	-1.0102	-0.7848
1.8610	-0.4545	-1.1111	-0.8000	-1.0111	-0.7847
1.8810	-0.4535	-1.1039	-0.7971	-1.0056	-0.7824
1.9010	-0.4518	-1.0882	-0.7912	-0.9939	-0.7780
1.9210	-0.4493	-1.0643	-0.7823	-0.9763	-0.7714
1.9410	-0.4457	-1.0332	-0.7707	-0.9533	-0.7625
1.9610	-0.4410	-0.9958	-0.7562	-0.9255	-0.7514
1.9810	-0.4350	-0.9531	-0.7392	-0.8937	-0.7381
2.0000	-0.4280	-0.9088	-0.7209	-0.8605	-0.7236

We can calculate $Z_1, Z_2, Z_3, Z_4, \ \omega_1, \ \omega_2$ in table A.3 and A.4

Table A.3 Etap Results for $t_{c1} = 1\ sec$. (Derived)

Time(sec.)	ω_1	ω_2	z_1	z_2	z_3	z_4
0.0200	0.0000	0.0000	0.2691	-0.0032	0.0357	-0.0175
0.0400	0.0000	0.0000	0.2691	-0.0032	0.0357	-0.0175
0.0600	0.0000	0.0000	0.2691	-0.0032	0.0357	-0.0175
0.0800	0.0000	0.0000	0.2691	-0.0032	0.0357	-0.0175
0.1000	0.0000	0.0000	0.2691	-0.0032	0.0357	-0.0175
0.1200	0.0000	0.0000	0.2691	-0.0032	0.0357	-0.0175
0.1400	0.0000	0.0000	0.2691	-0.0032	0.0357	-0.0175
0.1600	0.0000	0.0000	0.2691	-0.0032	0.0357	-0.0175
0.1800	0.0000	0.0000	0.2691	-0.0032	0.0357	-0.0175
0.2000	0.0000	0.0000	0.2691	-0.0032	0.0357	-0.0175
0.2010	374.9000	-50.1014	0.0677	-0.6296	-0.0410	-0.2324
0.2210	0.1650	-3.7999	0.0622	-0.7144	-0.0364	-0.2077
0.2410	0.0300	-2.6901	0.0613	-0.7697	-0.0356	-0.2054
0.2610	0.0000	-2.0099	0.0614	-0.8098	-0.0358	-0.2095
0.2810	-0.0050	-1.6500	0.0617	-0.8424	-0.0361	-0.2142
0.3010	-0.0050	-1.5550	0.0619	-0.8732	-0.0365	-0.2188
0.3210	-0.0050	-1.6150	0.0622	-0.9051	-0.0368	-0.2234
0.3410	-0.0050	-1.7650	0.0624	-0.9401	-0.0372	-0.2284
0.3610	-0.0050	-1.9700	0.0627	-0.9791	-0.0375	-0.2337
0.3810	-0.0050	-2.1950	0.0630	-1.0226	-0.0378	-0.2394
0.4010	-0.0050	-2.4350	0.0632	-1.0710	-0.0382	-0.2455
0.4210	-0.0050	-2.6850	0.0634	-1.1244	-0.0386	-0.2519
0.4410	0.0000	-2.9450	0.0636	-1.1831	-0.0389	-0.2584
0.4610	-0.0050	-3.2100	0.0637	-1.2471	-0.0392	-0.2648
0.4810	0.0050	-3.4851	0.0638	-1.3168	-0.0394	-0.2710
0.5010	0.0050	-3.7550	0.0638	-1.3920	-0.0395	-0.2766
0.5210	0.0050	-4.0450	0.0636	-1.4732	-0.0395	-0.2815
0.5410	0.0100	-4.3400	0.0632	-1.5606	-0.0394	-0.2853
0.5610	0.0200	-4.6449	0.0628	-1.6543	-0.0391	-0.2874
0.5810	0.0200	-4.9604	0.0622	-1.7545	-0.0384	-0.2874
0.6010	0.0250	-5.2892	0.0613	-1.8617	-0.0377	-0.2849
0.6210	0.0300	-5.6252	0.0602	-1.9759	-0.0366	-0.2791
0.6410	0.0350	-5.9804	0.0588	-2.0976	-0.0353	-0.2693
0.6610	0.0450	-6.3399	0.0572	-2.2269	-0.0338	-0.2548
0.6810	0.0500	-6.7152	0.0554	-2.3640	-0.0318	-0.2348
0.7010	0.0550	-7.0895	0.0533	-2.5090	-0.0296	-0.2089
0.7210	0.0550	-7.4656	0.0509	-2.6618	-0.0270	-0.1767
0.7410	0.0600	-7.8400	0.0482	-2.8225	-0.0244	-0.1386
0.7610	0.0700	-8.1943	0.0456	-2.9904	-0.0213	-0.0952

0.7810	0.0650	305.6246	0.0428	3.1180	-0.0181	-0.0484
0.8010	0.0700	-8.8296	0.0400	2.9372	-0.0150	-0.0006
0.8210	0.0650	-9.0905	0.0372	2.7513	-0.0119	0.0455
0.8410	0.0650	-9.3044	0.0347	2.5614	-0.0089	0.0873
0.8610	0.0550	-9.4658	0.0323	2.3686	-0.0062	0.1224
0.8810	0.0500	-9.5749	0.0304	2.1742	-0.0039	0.1494
0.9010	0.0350	-9.6395	0.0288	1.9791	-0.0021	0.1673
0.9210	0.0200	-9.6656	0.0277	1.7843	-0.0010	0.1761
0.9410	0.0100	-9.6746	0.0274	1.5903	-0.0003	0.1763
0.9610	-0.0100	-9.6650	0.0276	1.3974	-0.0005	0.1684
0.9810	-0.0250	-9.6499	0.0285	1.2058	-0.0014	0.1534
1.0000	-0.0421	-9.6421	0.0300	1.0249	-0.0028	0.1335
1.0010	-129.6000	-786.9009	0.1407	0.4783	0.0716	0.2338
1.0210	-1.4800	-5.9200	0.1504	0.3992	0.0679	0.2028
1.0410	-1.8750	-6.6650	0.1659	0.3189	0.0610	0.1615
1.0610	-1.8850	-6.4400	0.1823	0.2442	0.0537	0.1204
1.0810	-1.8000	-6.1400	0.1989	0.1740	0.0463	0.0806
1.1010	-1.6849	-5.8701	0.2156	0.1070	0.0388	0.0418
1.1210	-1.5601	-5.6550	0.2322	0.0417	0.0313	0.0032
1.1410	-1.4400	-5.5200	0.2490	-0.0231	0.0236	-0.0356
1.1610	-1.3150	-5.5000	0.2664	-0.0894	0.0156	-0.0759
1.1810	-1.1799	-5.5950	0.2846	-0.1595	0.0069	-0.1191
1.2010	-1.0001	-5.7850	0.3038	-0.2360	-0.0026	-0.1668
1.2210	-0.7300	-6.0050	0.3237	-0.3216	-0.0133	-0.2207
1.2410	-0.3400	-6.2000	0.3437	-0.4188	-0.0249	-0.2819
1.2610	0.1500	-6.3250	0.3620	-0.5300	-0.0373	-0.3515
1.2810	0.7050	-6.3650	0.3762	-0.6572	-0.0498	-0.4298
1.3010	1.2449	-6.3400	0.3834	-0.8017	-0.0611	-0.5155
1.3210	1.6951	-6.2900	0.3812	-0.9636	-0.0690	-0.6050
1.3410	1.9749	-6.2597	0.3681	-1.1414	-0.0714	-0.6916
1.3610	2.0851	-6.3451	0.3453	-1.3328	-0.0666	-0.7647
1.3810	2.0500	-6.6549	0.3157	-1.5365	-0.0544	-0.8091
1.4010	1.9100	-7.3906	0.2827	-1.7555	-0.0363	-0.8038
1.4210	1.7350	-8.9143	0.2494	-2.0018	-0.0150	-0.7181
1.4410	1.5450	-12.0000	0.2180	-2.3041	0.0072	-0.5154
1.4610	1.3700	-18.2300	0.1895	-2.7246	0.0281	-0.2032
1.4810	1.2000	286.0900	0.1643	2.9480	0.0468	0.1055
1.5010	1.0450	-31.4002	0.1428	2.2776	0.0626	0.3111
1.5210	0.8800	-22.6951	0.1251	1.7884	0.0752	0.4173
1.5410	0.6800	-14.7700	0.1116	1.4659	0.0845	0.4593
1.5610	0.4350	-10.7350	0.1025	1.2334	0.0903	0.4622
1.5810	0.1300	-8.8800	0.0984	1.0491	0.0929	0.4417
1.6010	-0.2500	-8.0750	0.0992	0.8934	0.0925	0.4069
1.6210	-0.6800	-7.7950	0.1050	0.7569	0.0895	0.3636
1.6410	-1.1450	-7.7850	0.1152	0.6343	0.0844	0.3157

1.6610	-1.5900	-7.8750	0.1291	0.5225	0.0778	0.2656
1.6810	-1.9600	-7.9650	0.1459	0.4192	0.0700	0.2148
1.7010	-2.2100	-7.9800	0.1649	0.3228	0.0615	0.1639
1.7210	-2.3100	-7.9000	0.1853	0.2314	0.0524	0.1135
1.7410	-2.2700	-7.6900	0.2064	0.1441	0.0430	0.0635
1.7610	-2.1250	-7.4400	0.2280	0.0594	0.0333	0.0138
1.7810	-1.9399	-7.2500	0.2501	-0.0247	0.0233	-0.0368
1.8010	-1.7451	-7.2750	0.2735	-0.1119	0.0126	-0.0901
1.8210	-1.5100	-7.5350	0.2986	-0.2073	0.0005	-0.1497
1.8410	-1.1250	-7.9950	0.3258	-0.3175	-0.0135	-0.2195
1.8610	-0.4850	-8.5350	0.3542	-0.4501	-0.0300	-0.3044
1.8810	0.4600	-9.0900	0.3801	-0.6152	-0.0487	-0.4098
1.9010	1.6550	-9.6900	0.3960	-0.8262	-0.0678	-0.5413
1.9210	2.8700	-10.4746	0.3901	-1.0990	-0.0811	-0.6995
1.9410	3.7500	-11.9101	0.3518	-1.4505	-0.0763	-0.8644
1.9610	4.0150	-15.2105	0.2841	-1.9027	-0.0423	-0.9486
1.9810	3.6450	-24.2749	0.2084	-2.5368	0.0112	-0.5964
2.0000	2.8579	286.2000	0.1497	2.7880	0.0562	0.2741

Table A.4 Etap Results for $t_{c2} = 0.6\ sec.$ (Derived)

Time(sec.)	ω_1	ω_2	z_1	z_2	z_3	z_4
0.0200	0.0000	0.0000	0.2691	-0.0032	0.0357	-0.0175
0.0400	0.0000	0.0000	0.2691	-0.0032	0.0357	-0.0175
0.0600	0.0000	0.0000	0.2691	-0.0032	0.0357	-0.0175
0.0800	0.0000	0.0000	0.2691	-0.0032	0.0357	-0.0175
0.1000	0.0000	0.0000	0.2691	-0.0032	0.0357	-0.0175
0.1200	0.0000	0.0000	0.2691	-0.0032	0.0357	-0.0175
0.1400	0.0000	0.0000	0.2691	-0.0032	0.0357	-0.0175
0.1600	0.0000	0.0000	0.2691	-0.0032	0.0357	-0.0175
0.1800	0.0000	0.0000	0.2691	-0.0032	0.0357	-0.0175
0.2000	0.0000	0.0000	0.2691	-0.0032	0.0357	-0.0175
0.2010	374.9000	-50.1014	0.0677	-0.6296	-0.0410	-0.2324
0.2210	0.1650	-3.7999	0.0622	-0.7144	-0.0364	-0.2077
0.2410	0.0300	-2.6901	0.0613	-0.7697	-0.0356	-0.2054
0.2610	0.0000	-2.0099	0.0614	-0.8098	-0.0358	-0.2095
0.2810	-0.0050	-1.6500	0.0617	-0.8424	-0.0361	-0.2142
0.3010	-0.0050	-1.5550	0.0619	-0.8732	-0.0365	-0.2188
0.3210	-0.0050	-1.6150	0.0622	-0.9051	-0.0368	-0.2234
0.3410	-0.0050	-1.7650	0.0624	-0.9401	-0.0372	-0.2284
0.3610	-0.0050	-1.9700	0.0627	-0.9791	-0.0375	-0.2337
0.3810	-0.0050	-2.1950	0.0630	-1.0226	-0.0378	-0.2394
0.4010	-0.0050	-2.4350	0.0632	-1.0710	-0.0382	-0.2455
0.4210	-0.0050	-2.6850	0.0634	-1.1244	-0.0386	-0.2519
0.4410	0.0000	-2.9450	0.0636	-1.1831	-0.0389	-0.2584
0.4610	-0.0050	-3.2100	0.0637	-1.2471	-0.0392	-0.2648
0.4810	0.0050	-3.4851	0.0638	-1.3168	-0.0394	-0.2710
0.5010	0.0050	-3.7550	0.0638	-1.3920	-0.0395	-0.2766
0.5210	0.0050	-4.0450	0.0636	-1.4732	-0.0395	-0.2815
0.5410	0.0100	-4.3400	0.0632	-1.5606	-0.0394	-0.2853
0.5610	0.0200	-4.6449	0.0628	-1.6543	-0.0391	-0.2874
0.5810	0.0200	-4.9604	0.0622	-1.7545	-0.0384	-0.2874
0.6000	0.0211	-5.2782	0.0613	-1.8561	-0.0377	-0.2851
0.6010	-347.2992	652.5943	0.3212	-0.5963	-0.0263	-0.3497
0.6210	-2.2600	-3.7550	0.3480	-0.5994	-0.0364	-0.3766
0.6410	-0.7501	-2.1450	0.3594	-0.6159	-0.0415	-0.3946
0.6610	-0.1449	-2.0450	0.3663	-0.6470	-0.0456	-0.4164
0.6810	0.1400	-2.0600	0.3709	-0.6864	-0.0496	-0.4412
0.7010	0.2900	-1.9800	0.3740	-0.7287	-0.0531	-0.4666
0.7210	0.3451	-1.8050	0.3756	-0.7701	-0.0561	-0.4905
0.7410	0.3550	-1.5350	0.3763	-0.8072	-0.0584	-0.5114
0.7610	0.3100	-1.2000	0.3761	-0.8376	-0.0600	-0.5280
0.7810	0.2400	-0.8200	0.3757	-0.8592	-0.0609	-0.5393

0.8010	0.1401	-0.4050	0.3751	-0.8707	-0.0613	-0.5451
0.8210	0.0250	0.0250	0.3746	-0.8712	-0.0611	-0.5449
0.8410	-0.0850	0.4750	0.3745	-0.8601	-0.0604	-0.5385
0.8610	-0.2050	0.9201	0.3743	-0.8378	-0.0592	-0.5261
0.8810	-0.3100	1.3700	0.3740	-0.8045	-0.0572	-0.5076
0.9010	-0.3951	1.8150	0.3730	-0.7613	-0.0546	-0.4833
0.9210	-0.4450	2.2400	0.3711	-0.7095	-0.0510	-0.4537
0.9410	-0.4650	2.6450	0.3676	-0.6508	-0.0464	-0.4196
0.9610	-0.4300	3.0250	0.3623	-0.5870	-0.0409	-0.3818
0.9810	-0.3500	3.3600	0.3549	-0.5202	-0.0345	-0.3417
1.0010	-0.2150	3.6500	0.3456	-0.4522	-0.0275	-0.3003
1.0210	-0.0550	3.8800	0.3344	-0.3847	-0.0201	-0.2589
1.0410	0.1401	4.0350	0.3220	-0.3192	-0.0127	-0.2185
1.0610	0.3250	4.1200	0.3088	-0.2565	-0.0052	-0.1797
1.0810	0.5050	4.1300	0.2954	-0.1974	0.0019	-0.1431
1.1010	0.6450	4.0850	0.2820	-0.1420	0.0087	-0.1090
1.1210	0.7549	3.9849	0.2690	-0.0904	0.0150	-0.0773
1.1410	0.8301	3.8550	0.2566	-0.0423	0.0209	-0.0478
1.1610	0.8850	3.7051	0.2450	0.0025	0.0263	-0.0206
1.1810	0.9050	3.5449	0.2340	0.0443	0.0314	0.0048
1.2010	0.9100	3.3750	0.2237	0.0833	0.0360	0.0282
1.2210	0.8950	3.1700	0.2142	0.1193	0.0403	0.0498
1.2410	0.8600	2.9400	0.2056	0.1523	0.0441	0.0694
1.2610	0.7950	2.6601	0.1980	0.1820	0.0475	0.0869
1.2810	0.7100	2.3300	0.1914	0.2078	0.0504	0.1020
1.3010	0.6000	1.9500	0.1860	0.2294	0.0528	0.1145
1.3210	0.4750	1.5250	0.1818	0.2462	0.0546	0.1242
1.3410	0.3350	1.0650	0.1790	0.2580	0.0559	0.1310
1.3610	0.1849	0.5850	0.1774	0.2644	0.0565	0.1345
1.3810	0.0401	0.0900	0.1773	0.2653	0.0567	0.1350
1.4010	-0.1150	-0.3950	0.1783	0.2607	0.0561	0.1323
1.4210	-0.2600	-0.8700	0.1807	0.2509	0.0550	0.1266
1.4410	-0.3951	-1.3100	0.1843	0.2362	0.0534	0.1181
1.4610	-0.5199	-1.7150	0.1890	0.2170	0.0513	0.1070
1.4810	-0.6250	-2.0650	0.1948	0.1940	0.0488	0.0936
1.5010	-0.7100	-2.3650	0.2015	0.1676	0.0458	0.0782
1.5210	-0.7750	-2.5950	0.2090	0.1387	0.0425	0.0612
1.5410	-0.8200	-2.7700	0.2170	0.1077	0.0389	0.0428
1.5610	-0.8300	-2.8900	0.2258	0.0753	0.0351	0.0234
1.5810	-0.8350	-2.9600	0.2347	0.0417	0.0310	0.0032
1.6010	-0.8151	-2.9950	0.2440	0.0074	0.0268	-0.0176
1.6210	-0.7850	-2.9900	0.2535	-0.0272	0.0226	-0.0387
1.6410	-0.7400	-2.9651	0.2630	-0.0622	0.0182	-0.0603
1.6610	-0.6850	-2.9049	0.2725	-0.0971	0.0138	-0.0819
1.6810	-0.6151	-2.8150	0.2819	-0.1317	0.0094	-0.1035

1.7010	-0.5400	-2.6950	0.2910	-0.1657	0.0050	-0.1248
1.7210	-0.4550	-2.5200	0.2996	-0.1984	0.0008	-0.1455
1.7410	-0.3649	-2.3051	0.3075	-0.2293	-0.0032	-0.1650
1.7610	-0.2800	-2.0350	0.3145	-0.2574	-0.0068	-0.1828
1.7810	-0.1950	-1.7200	0.3205	-0.2819	-0.0098	-0.1983
1.8010	-0.1300	-1.3550	0.3251	-0.3018	-0.0123	-0.2109
1.8210	-0.0700	-0.9500	0.3283	-0.3162	-0.0141	-0.2201
1.8410	-0.0200	-0.5250	0.3300	-0.3246	-0.0151	-0.2254
1.8610	0.0150	-0.0850	0.3302	-0.3264	-0.0153	-0.2264
1.8810	0.0500	0.3600	0.3289	-0.3215	-0.0147	-0.2232
1.9010	0.0850	0.7850	0.3262	-0.3102	-0.0132	-0.2159
1.9210	0.1250	1.1950	0.3221	-0.2929	-0.0109	-0.2049
1.9410	0.1800	1.5550	0.3168	-0.2707	-0.0082	-0.1908
1.9610	0.2350	1.8700	0.3104	-0.2444	-0.0048	-0.1741
1.9810	0.2999	2.1350	0.3031	-0.2150	-0.0011	-0.1556
2.0000	0.3684	2.3316	0.2956	-0.1852	0.0027	-0.1369

APPENDIX B

Matlab Code

Calculation the admittances and P parameters:

```
clear all; format compact ;clc;
%      From  To     R         X
zdata=[1     6    0.000    0.05
       2     7    0.000    0.03
       6     3    0.000    0.105
       6     5    0.000    0.225
       7     4    0.000    0.125
       3     4    0.000    0.175
       3     5    0.000    0.215 ];
Y=ybus(zdata);
Y1=Y(1:5,1:5);Y2=Y(1:5,6:end);Y3=Y(6:end,1:5);Y4=Y(6:end,6:end);
Ybus=Y1-Y2*inv(Y4)*Y3;
 [theta,B]=cart2pol(real(Ybus),imag(Ybus));
Ybus;
v=[1.10 1.10 1.044 1.0652 1.0302];
ds=[0 -17.22 -13.32 -17.37 -14.52];
dsr=degtorad(ds);
m=[0.5 0   0   0   0
   0   0.4 0   0   0
   0   0   0   0   0
   0   0   0   0   0
   0   0   0   0   0];

D=[0.2     0      0       0      0
   0       0.1    0       0      0
   0       0      0.25    0      0
   0       0      0      0.25    0
   0       0      0       0     0.2];

F=[1     1    0    0    0
   0     0    1    0    0
  -1     0    0    1    1
   0     0   -1   -1    0
   0    -1    0    0   -1];

Kt=[1    0    0    0   -1
    0    1    0    0   -1
    0    0    1    0   -1
    0    0    0    1   -1];

Gt=[1  0  -1  0
    1  0   0  0
    0  1  0  -1
    0  0  1  -1
    0  0  1  0];

Mg=m(1:2,1:2);Dg=D(1:2,1:2);Dl=D(3:end,3:end);
Fg=F(1:2,1:end);Fl=F(3:end,1:end);
K=Kt';Ktg=Kt(1:4,1:2);Kg=Ktg';Ktl=Kt(1:end,3:end);
```

```
for i=1:2

l(i,i)=m(i,i)/D(i,i);

end
for i=1:5
    for j=1:5
        c(i,j)=v(i)*v(j)*B(i,j);
    end
end
c=[v(1)*v(3)*B(1,3) v(1)*v(5)*B(1,5) v(2)*v(4)*B(2,4)
v(3)*v(4)*B(3,4) v(3)*v(5)*B(3,5)];
phr=[dsr(1)-dsr(3) dsr(1)-dsr(5) dsr(2)-dsr(4) dsr(3)-dsr(4)
dsr(3)-dsr(5)]

P22=inv(Kt*inv(D)*K);
theta_max=5;

P11=theta_max*Mg+Mg*inv(Dg)*(Kg*P22*Ktg-Dg)*inv(Dg)*Mg;
P12=Mg*inv(Dg)*Kg*P22;
P21=P12';
P=[P11       P12
   P21      P22];

eig(P)

Q=P22-P12'*inv(P11)*P12
```

Calculation the region of attraction:

```
clear all; clc;
phi=[0.232477856365645 0.253421807389577 0.002617993877991
0.070685834705770 0.020943951023932];
sm=-pi-2*phi'; sM=pi-2*phi'; se=[sm sM];
vmin=1e10; smin=sM;
h=pi/10;
for s5=sm(5):h:sM(5)
    for s4=sm(4):h:sM(4)
        for s3=sm(3):h:sM(3)
            for k=1:2
                s1=se(1,k);
                s2=s1+s5;
                if s2>=sm(2) && s2<=sM(2)
                    s=[s1 s2 s3 s4 s5]; vL=vmin; sL=smin;
                    [vmin,smin]=Lia(vL,sL,s);
                end
            end
            for k=1:2
                s2=se(2,k);
                s1=s2-s5;
                if s1>=sm(1) && s1<=sM(1)
                    s=[s1 s2 s3 s4 s5]; vL=vmin; sL=smin;
                    [vmin,smin]=Lia(vL,sL,s);
                end
            end
```

```
            end
            for k=1:2
                s3=se(3,k);
                for s2=sm(2):h:sM(2)
                    s1=s2-s5;
                    if s1>=sm(1) && s1<=sM(1)
                        s=[s1 s2 s3 s4 s5]; vL=vmin; sL=smin;
                        [vmin,smin]=Lia(vL,sL,s);
                    end
                end
            end
        end
        for k=1:2
            s4=se(4,k);
            for s3=sm(3):h:sM(3)
                for s2=sm(2):h:sM(2)
                    s1=s2-s5;
                    if s1>=sm(1) && s1<=sM(1)
                        s=[s1 s2 s3 s4 s5]; vL=vmin; sL=smin;
                        [vmin,smin]=Lia(vL,sL,s);
                    end
                end
            end
        end
    end
    for k=1:2
        s5=se(5,k);
        for s4=sm(4):h:sM(4)
            for s3=sm(3):h:sM(3)
                for s2=sm(2):h:sM(2)
                    s1=s2-s5;
                    if s1>=sm(1) && s1<=sM(1)
                        s=[s1 s2 s3 s4 s5]; vL=vmin; sL=smin;
                        [vmin,smin]=Lia(vL,sL,s);
                    end
                end
            end
        end
    end
```