



# **Improvement of Electrical Power System Dynamic Stability Using Riccati Matrix Method**

by

**Norfadilah Binti Rosle**  
**1432221146**

A dissertation submitted in partial fulfillment of the requirements for the  
degree of Master of Science Electrical Power Engineering

**School of Electrical System**  
**UNIVERSITI MALAYSIA PERLIS**

2015

# UNIVERSITI MALAYSIA PERLIS

## DECLARATION OF DISSERTATION

Author's full name : Norfadilah Binti Rosle  
Date of birth : 26<sup>th</sup> July 1986  
Title : Improvement of Electrical Power System Dynamic  
Stability Using Riccati Matrix Method  
Academic Session : 2014-S2

I hereby declare that this dissertation becomes the property of Universiti Malaysia Perlis (UniMAP) and to be placed at the library of UniMAP. This dissertation is classified as:

- CONFIDENTIAL** (Contains confidential information under the Official Secret Act 1972)
- RESTRICTED** (Contains restricted information as specified by the organization where research was done)
- OPEN ACCESS** I agree that my thesis is to be made immediately available as hard copy or on-line open access (full text)

I, the author, give permission to the UniMAP to reproduce this dissertation in whole or in part for the purpose of research or academic exchange only (except during a period of \_\_\_\_\_ years, if so requested above).

Certified by:

\_\_\_\_\_  
**SIGNATURE**

860726-30-5314

**(NEW IC NO. / PASSPORT NO.)**

Date: 13 March 2015

\_\_\_\_\_  
**SIGNATURE OF SUPERVISOR**

Dr. Muhammad Irwanto

**NAME OF SUPERVISOR**

Date: 13 March 2015

## **ACKNOWLEDGEMENT**

Assalammualaikum w.b.t

First and foremost, I would like to express my sincere gratitude to Dr. Irwanto for his guidance and advice. I can't say thank you enough for his tremendous support and help. Without his encouragement and guidance this research would not have materialized. His willingness to motivate me contributed tremendously to this research. Besides, I would like to take this opportunity to thank to the Centre for Graduate Studies (CGS) of Universiti Malaysia Perlis (UniMAP) for offering this subject, Electrical Power Engineering. Without offering this subject, I may not able to be here and study this challenging subject. Also, I would like to thank the authority of School of Electrical System (UniMAP) for providing a good environment and facilities to complete this research. Finally, an honorable mention goes to my family and friends for their understandings and supports in completing this research. Without helps of the particular that mentioned above, I would face many difficulties while doing this research. Thank you.

## **TABLE OF CONTENTS**

	<b>PAGE</b>
<b>DISSERTATION DECLARATION</b>	i
<b>ACKNOWLEDGEMENT</b>	ii
<b>TABLE OF CONTENTS</b>	iii
<b>LIST OF TABLES</b>	vi
<b>LIST OF FIGURES</b>	vii
<b>LIST OF ABBREVIATIONS</b>	ix
<b>LIST OF SYMBOLS</b>	xi
<b>ABSTRAK</b>	xiii
<b>ABSTRACT</b>	xiv
<b>CHAPTER 1 INTRODUCTION</b>	
1.1 Introduction	1
1.2 Problem Statement	7
1.3 Objectives	7
1.4 Scope and Significance of Project	8
1.5 Dissertation Organization	8
<b>CHAPTER 2 LITERATURE REVIEW</b>	
2.1 Overview	10
2.2 Critical Review of Previous Work	10
2.2.1 Improvement of Dynamic Stability by Using Power System Stability (PSS) and Flexible AC Transmission System (FACTS)	11
2.2.2 Dynamic Power System Stability by Using Energy Storage System	17
2.2.3 Linear Optimal Control for Dynamic Power System Stability	19

2.2.4 Fuzzy Logic Power System Stabilizer in Dynamic Power System Stability	20
2.3 Basic Structure of Electrical Power System	22
2.4 Power System Stability	25
2.5 Low Frequency Oscillation	27
2.6 Heffron Philips Constant [ $K_1$ , $K_2$ , $K_3$ , $K_4$ , $K_5$ and $K_6$ ]	28
<b>CHAPTER 3 METHODOLOGY</b>	
3.1 Introduction	30
3.2 Research Framework	30
3.3 Modeling of a single machine to an infinite bus (SMIB)	33
3.3.1 Equation for parameter $K_1$ to $K_6$	33
3.3.2 State space model of a single machine infinite bus (SMIB)	38
3.3.3 Block Diagram Representation	42
3.3.4 MATLAB Simulink Model Of A Single Machine Infinite Bus (SMIB) Without Riccati Matrix	45
3.4 SMIB Power System Model Including Gain From Riccati Matrix Method	46
3.5 Obtaining the Initial Parameter for the Power System	51
3.6 Techniques of Stability Evaluation	53
3.6.1 Stability Evaluation Using Eigenvalues Technique	53
3.6.2 Stability Evaluation Using Time-Domain Simulation Technique	54
<b>CHAPTER 4 RESULT AND DISCUSSION</b>	
4.1 Overview	55
4.2 Dynamic Stability Of Single Machine Infinite Bus (SMIB) Without Riccati Matrix	55
4.2.1 Stability Evaluation Using Eigenvalues Technique	56
4.2.2 Stability Evaluation Using Time Domain Technique	57
4.3 Dynamic Stability Of Single Machine Infinite Bus (SMIB) With Riccati	

Matrix	62
4.3.1 Stability Evaluation Using Eigenvalues Technique	62
4.3.2 Stability Evaluation Using Time Domain Technique	64
<b>CHAPTER 5 CONCLUSIONS AND FUTURE WORK</b>	
5.1 Conclusion	71
5.2 Future Work	72
<b>REFERENCES</b>	73
<b>APPENDIX A</b>	76

©This item is protected by original copyright

## LIST OF TABLES

NO.	PAGE
4.1 Constant [K1-K6] for SMIB	56
4.2 Eigenvalues Data For SMIB Without Riccati Matrix	56
4.3 Damping oscillation for rotor speed (p.u)	60
4.4 Damping oscillation for rotor angle (p.u)	61
4.5 Gains and Eigenvalues data for SMIB with Riccati matrix	62
4.6 Summary of SMIB with and without Riccati matrix for $\pm 0.1$ p.u disturbance	69

©This item is protected by original copyright

## LIST OF FIGURES

NO.	PAGE
1.1 Classification of Power System Stability	2
1.2 Local mode oscillation	4
1.3 Mechanical and Electrical Torque Applied to the Shaft	5
2.1 Single Machine Infinite Bus with STATCOM	15
2.2 Single Machine Infinite Bus with UPFC	16
2.3 SVeC Block Diagram with Design PID Controller	17
2.4 A power system installed with a PMSG based STATCOM stabilizer	18
2.5 FLPSS Model	21
2.6 A basic structure of a simplified power system	22
2.7 Elementary diagram of transmission and distribution system	24
2.8 Linearized block diagram of SMIB	29
3.1 Flow chart of the research	32
3.2 Single machine infinite bus	38
3.3 The Torque Angle Loop of Synchronous Machine	43
3.4 Flux Decay Model	43
3.5 Excitation System	44
3.6 Overall Block Diagram of the SMIB System	44
3.7 MATLAB Simulink Model of the SMIB with Exciter Power System	45
3.8 MATLAB Simulink Model of the SMIB with additional gains of Riccati Method in red dotted line	50
4.1 Oscillation of Rotor Speed for 0.1 p.u	58
4.2 Oscillation of Rotor Speed for -0.1 p.u	58
4.3 Oscillation of Rotor Angle for 0.1 p.u	59

4.4 Oscillation of Rotor Angle for -0.1 p.u	60
4.5 Oscillation of Rotor Speed with and without Riccati for 0.1 p.u	64
4.6 Overshoot and settling time for rotor speed at 0.1 p.u disturbance	65
4.7 Oscillation of Rotor Speed with and without Riccati for -0.1 p.u	65
4.8 Overshoot and settling time for rotor speed at -0.1 p.u disturbance	66
4.9 Oscillation of Rotor Angle with and without Riccati for 0.1 p.u	67
4.10 Overshoot and settling time for rotor angle at 0.1 p.u disturbance	67
4.11 Oscillation of Rotor Angle with and without Riccati for -0.1 p.u	6
4.12 Overshoot and settling time for rotor angle at -0.1 p.u disturbance	69

©This item is protected by original copyright

## LIST OF ABBREVIATIONS

ANN	Artificial Neural Networks
AVR	Automatic Voltage Regulator
BESS	Battery Energy Storage System
CARE	Continuous Time Algebraic Riccati equation
DAE	Differential Algebraic Equation
DARE	Discrete Time Algebraic Riccati equation
ESS	Energy Storage System
ETLOBA	Teaching Learning Based Optimization
FACTS	Flexible AC Transmission System
FLPSS	Fuzzy Logic Power System Stabilizer
ISE	Integral of Squared Error
LFO	Low Frequency Oscillation
LOC	Linear Optimal Control
MATLAB	Mathematic Laboratory
PI	Proportional Integral
PID	Proportional Integral Derivative
PMSG	Permanent Magnet Synchronous Generator
PSS	Power System Stabilizer
SISO	Single In Single Out
SMIB	Single Machine Infinite Bus
SSSC	Static Synchronous Series Compensator
STATCOM	Static Compensator

SVC	Static Var Compensator
SVeC	Static Vectorial Compensator
TCSC	Thyristor Controlled Series Capacitor
UPFC	Unified Power Flow Controller

©This item is protected by original copyright

## LIST OF SYMBOLS

$\delta$	Rotor Angle
$f$	Frequency Oscillation in Hz
$\lambda$	System Eigenvalue
$\sigma$	Real Part of Eigenvalue
$\zeta$	Damping Ratio
$m_b$	Boosting modulation index converter
$m_e$	Excitation modulation index converter
$\omega$	Rotor Speed
$\omega_b$	Rotor Speed Deviation (base speed)
$\omega_s$	Rotor Speed of Synchronous Generator
$D$	Damping Coefficient
$E_{fd}$	Excitation System Voltage in p.u
$E'_q$	Voltage Proportional to Field Flux Linkage
$H$	Inertia Constant
$I_d, I_q$	d and q axis Generator Currents
$K_A$	Exciter Gain
$K_D$	Damping Torque Coefficient
$R_e$	Transmission Line Resistance
$T_A$	Exciter Time Constant
$T'_{do}$	Open Circuit d-axis Time Constant in sec
$T_e$	Electric Torque
$T_M$	Mechanical Power Input in p.u

$T_p$	Peak Time
$T_s$	Settling Time
$V_d, V_q$	d and q axis Generator Voltages
$V_{ref}$	Exciter Reference Input
$V_t$	Terminal Voltage
$V_\infty$	Infinite Bus Voltage
$X_d$	d-axis Synchronous Reactance in p.u
$X'_d$	d-axis Transient Reactance in p.u
$X_e$	Transmission Line Reactance
$X_q$	q-axis Synchronous Reactance in p.u
$X'_q$	q-axis Transient Reactance in p.u

©This item is protected by original copyright

## **menggunakan Kaedah Matrik Riccati**

### **ABSTRAK**

Ayunan frekuensi rendah di dalam sistem kuasa wujud apabila terdapat sedikit gangguan yang dikenali sebagai gangguan kecil dan menjadi tajuk utama di dalam tesis ini. Disebabkan gangguan kecil ini, sistem kuasa mengalami masalah ayunan frekuensi yang serius. Di dalam kestabilan dinamik sistem kuasa, ayunan frekuensi positif adalah sangat penting. Dengan menggunakan gandaan optimum yang dihasilkan daripada kaedah matrik Riccati, ayunan tersebut boleh berayun dengan sempurna dan kestabilan sistem kuasa dapat ditingkatkan. Kaedah matrik Riccati digunakan untuk meningkatkan kestabilan redaman ayunan di dalam sistem kuasa. Kajian ini membentangkan tentang rekabentuk mesin tunggal kepada bas tak terhingga dengan penambahan gandaan optimum daripada kaedah matrik Riccati untuk meningkatkan redaman di dalam ayunan frekuensi rendah. Analisis kestabilan 'eigenvalues' dan analisis domain masa di gunakan di dalam keseluruhan sistem. MATLAB Simulink digunakan untuk merekabentuk kaedah matrik Riccati supaya ciri-ciri dan karakter sistem kuasa dapat ditingkatkan disamping dapat meningkatkan kestabilan sistem. Simulasi yang terhasil telah dilakukan untuk membuktikan keberkesanan dan keteguhan rekabentuk kaedah matrik Riccati. Analisis dan simulasi menunjukkan keberkesanan kaedah matrik Riccati telah meningkatkan kestabilan sistem kuasa elektrik dinamik.

©This item is protected by digital copyright

## Stability using Riccati Matrix Method

### ABSTRACT

Low frequency oscillations appear when a small disturbance occurs in an interconnected multi-machine power system and becomes one of the major subjects concerning in power system studies. Due to small disturbances, power systems experience these poorly damped low-frequency oscillations. In the dynamic electrical power system stability, the positive damping oscillation is very important. By using the optimum gains that obtained from Riccati matrix method, these oscillations can be well damped and hence the system stability is enhanced. Riccati matrix method is used to enhance better system stability in damping oscillation power system. This research presents a design of a single machine to an infinite bus (SMIB) with additional optimum gain from Riccati matrix method to enhance the dynamic stability of power systems by improving the damping of the low frequency oscillations. Eigenvalues analysis and time domain analysis are applied to the overall system. MATLAB Simulink is used to design a Riccati matrix method to enhance the damping characteristic of power system to improve its stability. The dynamic simulations results are presented to show the effectiveness and robustness of the designed Riccati matrix method. Analysis and simulation have proved the effectiveness of a Riccati matrix method in order to improve the electrical power system dynamic stability.

# CHAPTER 1

## INTRODUCTION

### 1.1 Introduction

Power systems have developed from the original central generating station concept to a modern interconnected system with improved technologies affecting each part of the system separately. Recently, power systems are changing rapidly because of uncontrolled and high user demand. This situation facing a problem and needs the solution to maintain stability and reliability of the system (Ghafouri et al., 2007). In an electrical power system, there are one or more generating units, loads and power transmission lines including the associated equipments connected to it. There are needs for stable condition to ensure the system is running smoothly. Successful operation of a power system depends largely on the ability of power utility to provide a reliable and uninterrupted service to the loads.

Since 1920s, power system stability has been recognized as an important problem for secure system operation which is if the system is not fully secured, it will caused the instability in the power system such as major blackouts (Kundur et al., 2004). Power system stability may be generally defined as the characteristic of a power system that enables it to remain in a state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance (Kundur, 1994). The stability of the power system is concerned with the

behavior of the synchronous machines after they have been disturbed. The machines should return to their original state if the disturbance does not involve any net change in power but if an unbalance between the supply and demand is created by a change in load, in generation, or in network conditions, a new operating state is necessary. In other words, the system should remain operating in parallel and at the same speed if the system is stable in any case all interconnected synchronous machines.

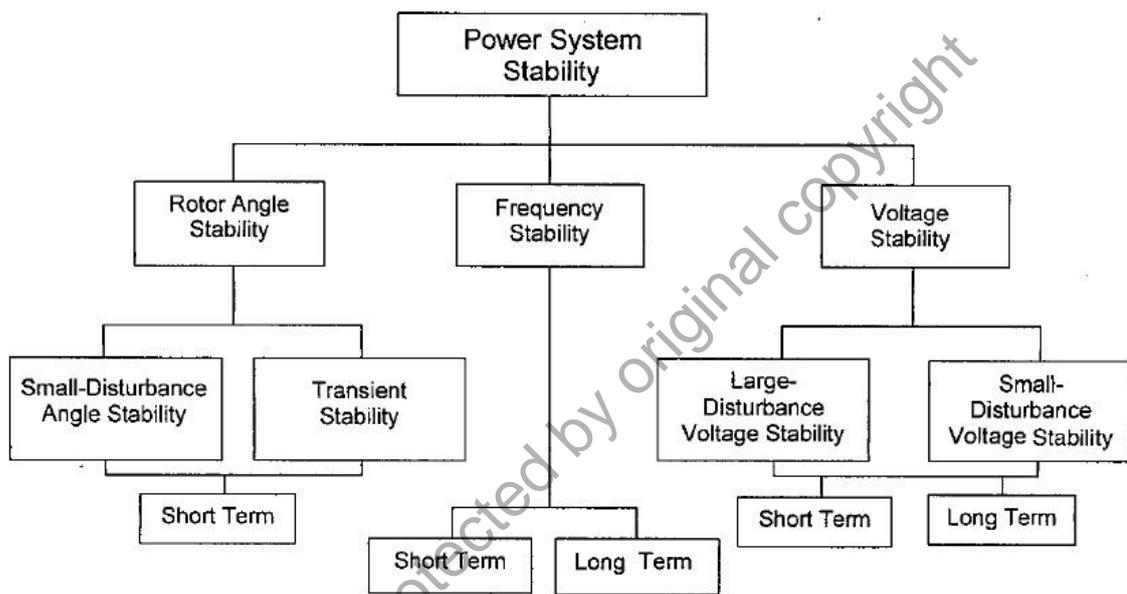


Figure 1.1: Classification of Power System Stability (Kundur et al., 2004).

Classification of power system stability can take in many forms, but for rotor angle stability they fallout into two main stability types which are transient stability and small signal stability as shown in Figure 1.1. The differences between stability types are referred to the size and effect disturbance to the system. Transient stability is the ability to maintain synchronism when the system is subjected to a large disturbance. The changes in the dynamic variables are large in the resulting system response and the nonlinear behavior of the system is important (Kundur, 1994). Small signal stability also known as dynamic stability is the ability of the system to maintain stability under small disturbance. Such disturbances occur continuously in the normal operation of a

power system due to small variations in load and generation. The disturbances are considered sufficiently small to permit the use of linearized system model in the analysis of the small signal stability.

In the evaluation of stability, the concern is the behavior of the power system when subjected to disturbance. The disturbance may be small or large. When the load changes take place continually in small disturbance, the system will adjust itself to the changing conditions. The system must supply the maximum amount of load to make the system operate satisfactory under these conditions. It must also be capable of surviving numerous disturbance of a severe nature, such as short-circuit of a transmission line, loss of large generator or load, or loss of a tie between two subsystems. Small disturbances can be divided into two types of instability which are oscillatory instability and non-oscillatory instability. In case of oscillatory instability, the rotor angle oscillates with increasing magnitude while in non-oscillatory instability, the rotor angle of a generator keeps on increasing. Switching on or off of small loads, line tripping and small generators tripping are one of examples of small load changes.

Load changes in the power system are one of the reasons of power system operating conditions being changed and it is affect the stability of the synchronous machine. These operating conditions which are obtained by either computer simulation or measurement need stability in the system. Therefore, a small-signal stability analysis should be conducted. Small-signal stability or the dynamic stability usually concerned as a problem of insufficient or poorly damping of system oscillations. These oscillations are undesirable even at low-frequencies, because they reduce the power transfer in the transmission line and sometimes introduce stress in the system (Anderson & Fouad, 1994).

In the power system secure operation, the positive damping oscillation is very important and needed in the operation (Najafi & Kazemi, 2006). Low frequency oscillations (LFO) in a large-scale power system is always attract an attention all researchers. Load changes and system faults are once again knows as the factors of low frequency oscillations. If the oscillations can be damped down in a short period, the system is a stable. The system become unstable when the oscillations is taken a long period of time goes to steady state or slowly increase in value resulting in synchronous machines running out-of-step (Tsang & Susanto,2003).

Low frequency oscillations appear when a small disturbance occurs in an interconnected multi-machine power system and becomes one of the major subjects concerning in power system studies. The small-signal stability can be improved in electrical multi-machine power system if these oscillations are sufficiently reduced (Abu tabak et al., 2008). Electromechanical oscillations can be divided into five modes which are interplant mode, local mode, inter-area mode, control mode and torsional modes between rotating plant, but two most critical types that of concern in low frequency oscillation are the local mode and the inter-area mode. The local mode is associated with a single unit or station with respect to the whole system, whereas the inter-area mode is associated with many units in an area with respect to other units in another area (Sauer & Pai, 1998). In this study, the analysis is done for local oscillations as shown in Figure 1.2.

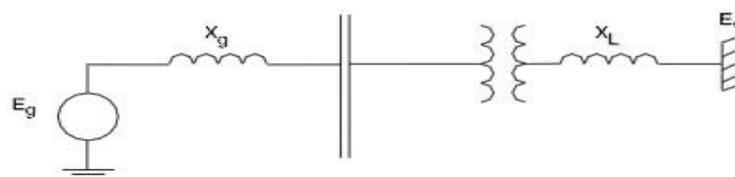


Figure 1.2: Local mode oscillation (Basler & Schaefer, 2008).

In local mode, one generator swings against the rest of the system at 1.0 to 2.0 Hz. The generator and the line are connected to the grid will gives impact to the oscillation. The rest of the system is normally modeled as a constant voltage source whose frequency is assumed to remain constant. This is known as the single-machine-infinite-bus (SMIB) model. The machine output and the impedance between the machine terminal and the infinite bus voltage are varies with the damping and frequency. The rotors of each synchronous machine in the system rotate at the same average electrical speed in an interconnected power system. The mechanical power applied by the prime mover is equal to the power delivered by the generator to the power system.

The mechanical torque is in the direction of rotation while an electrical torque is applied in a direction opposite of rotation to the shaft by the generator as shown in Figure 1.3. The electrical power out of the machine is change when the system is disturbed due to a fault or the load is changed quickly which is can change rapidly. Different with the mechanical power into the machine which is relatively slow to change after the system is disturbed (Basler & Schaefer, 2008).

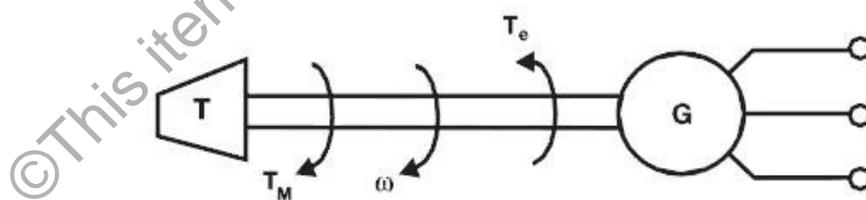


Figure 1.3: Mechanical and Electrical Torque Applied to the Shaft (Basler & Schaefer, 2008).

Power system stability also can be maintained with the excitation system speed of response. To increase the potential of a stable system, the response time must be decreased. Excitation system will impact to the stability of the power system either to

make the system is stable or unstable. Excitation system can help to reduce the damping torque by contribute the negative damping to oscillations (Basler & Schaefer, 2008). Thus, the power system has the potential to facing small signal instability.

In addition to the usual or conventional excitation control techniques and speed governors, Riccati matrix method is used to enhance better system stability in damping oscillation power system. The equation is named after Count Jacopo Francesco Riccati. Riccati matrix method always attract researcher to use it in many fields of control theory and involved in stability analysis, optimal control synthesis and model reduction (Suchomski, 2001; Tao & Deng, 2010). Riccati equation is used to refer the matrix equations with an analogous quadratic term. When an equation wants to solve and convert to matrix form, Riccati method is recommended to use because this method have too many ways in solving the differential equation. One of the solving ways is by using MATLAB. In MATLAB, there had commands for Riccati equation which occur in both continuous-time and discrete-time. In this research, Riccati method is used to find the optimum gain which is act as a stabilizer in the system. Continuous-time algebraic Riccati equation or known as CARE has many form of equation. In MATLAB, CARE computes the unique solution  $X$  of the algebraic Riccati equation and in quadratic terms but there are no higher-order terms. Compared with discrete-time algebraic Riccati equation or known as DARE which is arises in place of the CARE when studying discrete time systems, DARE is much complicated compare with CARE.

This method is used by most of the researchers to solve the stability problems with additional devices and combination techniques. However, there are no studies to simulate and prove the effectiveness of Riccati method in determining the optimum gain of parameters which is act as a stabilizer in the power system without any additional or combination technique. This project aims to analyze and obtain the optimum gain for

parameters of damping oscillation in SMIB by using Riccati matrix method in order to improve dynamic power system stability.

## **1.2 Problem Statement**

Modern power systems are highly complex and strongly nonlinear with the operating conditions vary over a wide range, thus it is quite difficult to design. Small disturbance in power system gives impact to the parameters changing in term of speed and angle. Parameters without optimum gain will makes low damping oscillation. Low or negative damping in a power system can lead to spontaneous appearance of large power oscillations.

A power system without stabilizer cannot be stable when a disturbance occurs. The stabilizer may comes with a different devices and technique. Different devices and techniques that used will result in different way in maintaining the stability of the power system. There are certain devices and technique, however they are costly and time consuming. The stabilizer that can gives the positive damping in fast and efficient is more better than the stabilizer that can produce the same result but in the high cost and time consuming.

## **1.3 Objectives**

This research is done based on the objectives as below:

1. To apply Riccati matrix method and obtain the optimum gains.
2. To observe the damping oscillation of rotor speed and rotor angle by using MATLAB Simulink software.
3. To compare the damping oscillation results between SMIB with and without applying Riccati matrix method.

## **1.4 Scope and Significance of Project**

Riccati matrix method is implemented to obtain the optimum gain for the system. The optimum gains will be acted as a stabilizer of the system which will be calculated and applied into the SMIB by using MATLAB Simulink. Once the system is developed, it will simulate and shows the real the damping oscillation of the speed and angle that can improve the damping system, which is important in dynamic power system.

Stability improvement of dynamic power system in the previous studies uses many techniques and devices such as Flexible AC Transmission System (FACTS) devices, conventional power system stabilizer or combination both of them, which are time consuming. Thus, through this research, the stabilizer will be developed using optimum gains that is obtained from Riccati matrix method which is fast and efficient. The optimum gains will help to stabilize the damping oscillation in dynamic power system efficiently especially for rotor speed and rotor angle.

## **1.5 Dissertation Organization**

The dissertation is organized into 5 chapters and 2 appendices. Each chapter begins with a introduction describing the points of the research as follows:

1. Chapter 1 is a brief overview of the development of dynamic power system, classification of power system stability and description of the small signal stability. Included is a problem statement, objectives and significance of the research.
2. Chapter 2 reviews the research of previous researcher had been done to improve the dynamic power system stability and covers some data or information that needed in the research. Before going to the next step, all info related to the research is reviewed and take as a references.

3. Chapter 3 is explains about the method, technique and processes of the research and steps taken to evaluate the stability by using three different techniques and how run the overall system using MATLAB Simulink and M-File.
4. Chapter 4 discusses the results obtained from the research which are having two different results. One is single machine infinite bus (SMIB) without Riccati matrix and other one is with Riccati matrix. Both system are analyzed and evaluated by using stability techniques.
5. Chapter 5 covers the conclusion for overall result of SMIB with and without Riccati matrix in order to improve the stability of dynamic electrical power system and the future work for this research is discussed.

©This item is protected by original copyright