Analysis of Dynamical Stability for Synchronous Generators Through Swing Equation

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2021

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A report submitted
in partial fulfillment of the requirements for the degree of
Bachelor of Electrical Engineering with Honours

Faculty of Electrical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2021

DECLARATION

I declare that this thesis entitled " Analysis of Dynamical Stability for Synchronous Generators Through Swing Equation " is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature :

Name : NUR DIANA IZZANI BINTI MASDZARIF

Date : 04/07/2021

APPROVAL

I hereby declare that I have checked this report entitled "Analysis of Dynamical Stability for Synchronous Generators Through Swing Equation" and in my opinion, this thesis it complies the partial fulfillment for awarding the award of the degree of Bachelor of Electrical Engineering with Honours.

Signature : ....

Supervisor Name : **DR. MUHAMMAD NIZAM BIN KAMARUDIN**

Date : **4 JULY 2021**

DEDICATIONS

I dedicate my work to my beloved mother and father.

ACKNOWLEDGEMENTS

All praises to the Most Gracious, Most Merciful for the strength and His blessings for me to complete this final year project during this whole 2 semesters. I am extremely grateful to those who have helped me throughout this project. First and foremost, I would like to express my biggest gratitude to Dr. Muhammad Nizam bin Kamarudin, my supervisor, for his countless hours of reading and encouraging, for his motivation, enthusiasms and immense knowledge. He contributed a lot to my project in terms of guiding, teaching, supporting and advising endlessly all the time during my completion of project. His guidance really helped me during executing this project. I could not have asked for a better one.

My journey during this final year project could not have been accomplished without the support from my fellow classmates, 4BEKG Section 3, and my fellow undergraduate students. A wonderful appreciation to all of them for their encouragement and assistance which helped me a lot at various occasions especially during my ups and downs. Also, not to be forgotten, a very thankful note should be sent towards my family especially my parents, Encik Masdzarif bin Mahat and Puan Jamilah binti Abd Aziz for their love, prayers, thoughts, motivational supports and sacrifices throughout my studies and this project. I would never be where I am right now if it were not because of them. Finally, I am eternally grateful to everyone for their dedication to ensure that my final year project runs smoothly and successfully.

ABSTRACT

The dynamics of synchronous generator is highly depending on synchronizing power coefficient, per unit inertia constant and damping coefficient. As such, the stability and transient performance of the synchronous generator through swing equation are also depending on these three parameters. This is because, any small changes in synchronizing power coefficient will affect the damping ratio and natural frequency of the generator and hence affect the transient performance. Thus, the need for studying the effect of synchronizing power coefficient towards the stability of synchronous generator through swing equation is a must. The designing of controller is also needed to improve dynamic stability and oscillation within stability range. Therefore, this research proposes to develop a mathematical model of synchronous generator through swing equation, to analyse the effect of synchronizing power coefficient towards synchronous generator's stability and the design of controller to analyze the stability of synchronous generator. The proposed methodology consists of five phases. Firstly, the development of swing equation, a mathematical model of synchronous generator which contains the three elements that affect the synchronous generator's dynamics. Second, the study on power angle curve where the steady-state stability limit will affect the swing equation. This combination of synchronous machine model equation with swing equation then led to the analysis of steady-state stability and its performance since it includes the damping coefficient and damper frequency. The fourth phase is the state feedback controller design by pole placement method and Linear Quadratic Regulator (LQR) method. In order to verify the stability and transient performance of synchronous generator, a simulation through MATLAB/SIMULINK software is used. It is observed that, the stability of the synchronous generator is highly depends on the value of synchronizing power coefficient, P_s since P_s affects the pole location of the synchronous generator. When P_s is positive, the system is in marginally stable. However, when P_s is negative, the system is unstable. For the controllers' design, there are pros and cons between these controllers. The state feedback controller by pole placement method has the shortest stabilizing time compared to LQR method. But the LQR controller produces lower energy while stabilizing the system. Thereby, LQR controller is better than state feedback controller by pole placement method.

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LIST OF ABBREVIATIONS

mmf	-	Magneto-motive force
LQR	-	Linear Quadratic Regulator
LFC	-	Load Frequency Control
IEEE	-	Institiute of Electrical and Electronics Engineers
RSG	-	Rotational Synchronous Generator
DC	-	Direct Current
AC	-	Alternating Current
PI	-	Proportional and Integral
PD	-	Proportional and Derivative
PID	-	Proportional Integral Derivative
PIC	-	Programmable Integrated Circuit
KCL	-	Kirchhoff Current Law
LHS	-	Left-Hand Side

LIST OF SYMBOLS

δ	-	Rotor angle/electrical power angle
V_t	-	Terminal bus voltage
V_{bus}	-	Infinite bus voltage
E	-	Excitation electromotive force
U	-	Stator end voltage
I	-	Armature current
r_a	-	Stator armature resistance
X_d	-	Synchronous reactance
J, kg/m^2	-	Rotational inertia
P_m	-	Mechanical power
P_e	-	Electromagnetic power
ω	-	Electric angular velocity
D	-	Constant damping system
$\Delta\omega$	-	Angular speed
P_{gen}	-	Generator true power
P_{load}	-	Load true power
Q_{gen}	-	Generator reactive power
Q_{load}	-	Load reactive power
r	-	Reference input
d	-	Processes disturbances
y	-	Output system of a controller
A	-	System matrix
B	-	Input matrix
C	-	Output matrix
D	-	Feed-forward matrix
$x'(t)$	-	Derivative of state vector
$x(t)$	-	State vector
$y(t)$	-	Output vector
$u(t)$	-	Input of control vector
K	-	Gain
U	-	Energy
J	-	Performance index
Q	-	Positive definite matrix
R	-	Positive definite matrix
T_e	-	Electromagnetic torque
ω_{sm}	-	Synchronous speed
T_m	-	Mechanical torque
T_a	-	Torque on rotor/Accelerating torque
θ_m	-	Angular displacement of rotor
δ_m	-	Rotor position/mechanical power angle
M	-	Inertia constant
W_k	-	Kinetic energy of rotating masses
p	-	Number of poles
S_B	-	Base power
H	-	Per unit inertia constant/H constant
$P_{m\,(pu)}$	-	Per unit mechanical power

$P_{e\,(pu)}$	-	Per unit electrical power
f_0	-	Frequency
δ	-	Electrical power angle
$\Delta\delta$	-	Small deviation in power angle
δ_0	-	Initial operating point of power angle
P_s	-	Synchronizing coefficient
ω_d	-	Damper frequency
ζ	-	Damping coefficient
ω_n	-	Natural frequency
D	-	Per unit damping power coefficient
ΔP	-	Small deviation in power
s	-	Poles
Z	-	Impedance

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

This chapter discusses the research background, motivation, problem statement, objectives, and scope of research.

1.1 Background

Synchronous generator may experience some disturbance due to acceleration and deceleration of a motor. Swing equation is a mathematical equation that can maintain stability in a synchronous generator. It represents the swings in the rotor angle, δ during disturbances. In other words, the swing equation describe a relative motion of a motor since during any disturbance, rotor will experience acceleration or deceleration with respect to the synchronously rotating air gap magneto-motive force (mmf). Some elements will be affected with the presence of this disturbance. For instance, the synchronizing power coefficient, per unit inertia constant and damping coefficient which can be observed from the swing equation. The synchronizing power coefficient effect is relatable to the stability as it is the quotient of shaft power of a motor by the load angle or angular displacement of the rotor. Next, the inertia constant also affects the equilibrium since it measures the ratio of kinetic energy of a rotor to the generator or machine power rating. External or internal disturbance which results in a system error is commonly found in control systems and it can be withstand with some stability by controlling the system voltage for example. In other words, the problem of stability is related with the behaviour and the action of the synchronous machines after a disturbance [1]. Hence, the swing equation is observed and a controller which functions to reduce the steady-state error is introduced. However, there are specific types of controllers that can be utilized specifically to observe the transient performance and stability of synchronous generators such as State Feedback Controller and Linear Quadratic Regulator (LQR) Controller. The stabilization can be achieved by designing the dynamic of a system through state feedback by using pole placement method. Meanwhile, the LQR also can give high performance and make the system stable. Therefore, stability will allow the system to reach the steady-state and to ensure that, after major disturbances, the system can tolerate and withstand the transient condition.

1.2 Motivation

Stability is a very important property in control system studies. Gaining system stability will allow the system to reach and remain in steady-state after some variations in the parameters of the system. In power system, stability study is important to avoid performance deterioration due to disturbance such as gradual power changes, sudden outage of a line and sudden application or removal of loads. To reach the stability studies for a rotor angle stability problem, the knowledge of a first-order differential equation relating the equilibrium condition between mechanical power from the prime mover and electrical power is a must. This equation is called a swing equation, where it relates the rotor angle to the equilibrium states of the mechanical torque (or power) and electrical torque (or power). This project aims to analyze a rotor angle stability of synchronous generators and to maintain and withstand its stability in a certain condition such as steady-state, dynamic and transient after some disturbances. Since stability problem is related with the behaviour and characteristic of synchronous machines after a disturbance, studies are conducted to analyse dynamical stability for synchronous generator through swing equation and by designing a controller for stability achievement.

1.3 Problem Statement

In synchronous generator, the relative motion between the rotor axis and synchronously rotating stator field axis is helpful in analysing stability. Any changes in rotor angle, δ results in change of real power, which ultimately affects the frequency. The swing equation therefore serves as the basis for modelling power system stability. Swing equation represents the equilibrium condition between mechanical power from the prime mover and electrical power. Dynamic of synchronous generator is highly depending on synchronizing power coefficient, per unit inertia constant and damping coefficient. As such, the stability and transient performance of the synchronous generator through swing equation are also depending on these three parameters. Any small changes in synchronizing power coefficient and per unit inertia constant will affect the damping ratio and natural frequency of the generator and hence affect the transient performance. As such, this research studies the effect of synchronizing coefficient towards the stability of synchronous generator through swing equation as well as to observe on how to maintain dynamic stability and the oscillations within stability range. Furthermore, the controller has been designed to improve the stabilization process and hence, to analyse the stability of synchronous generator.

1.4 Objective

The objectives of this research are:

i. To develop a mathematical model of synchronous generator through swing equation.

ii. To analyse the effect of synchronizing power coefficient towards stability of generator.

iii. To design a stabilizing function using pole placement and Linear Quadratic Regulator (LQR) for a synchronous generator and hence, conduct a comparative analysis between the two.

1.5 Scope

This research-based project covers the studies about modelling and analysis of rotor angle stability of a synchronous machine and important components in swing equation that affect the stability of a system as well as designing a controller to check the stability of a system. Research is focus on one-machine system or single-machine system connected to an infinite bus bar. For controllers, research is focus on designing the state feedback controller via pole placement method and Linear Quadratic Regulator (LQR) method. The result to this research is obtained by using MATLAB and SIMULINK software as a research tool.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This literature review explains about the past research and the project development which is relevant and use almost similar system with this project. The reviews are including the theory of power plant generation, power system stability with their sub series, synchronous machines and controllers.

2.2 Power Plant Generation System

Paper [2] stresses that power generation systems are generally considered as heat engines which turn heat input into work for the sustainable production of electricity. Burning fossil fuels (coal, oil and natural) and biomass, or harvesting thermal energy are the examples of heat input supply. Power generating plant or also referred as power station is classified into conventional and non-conventional as depicted in Figure 2.1 below.

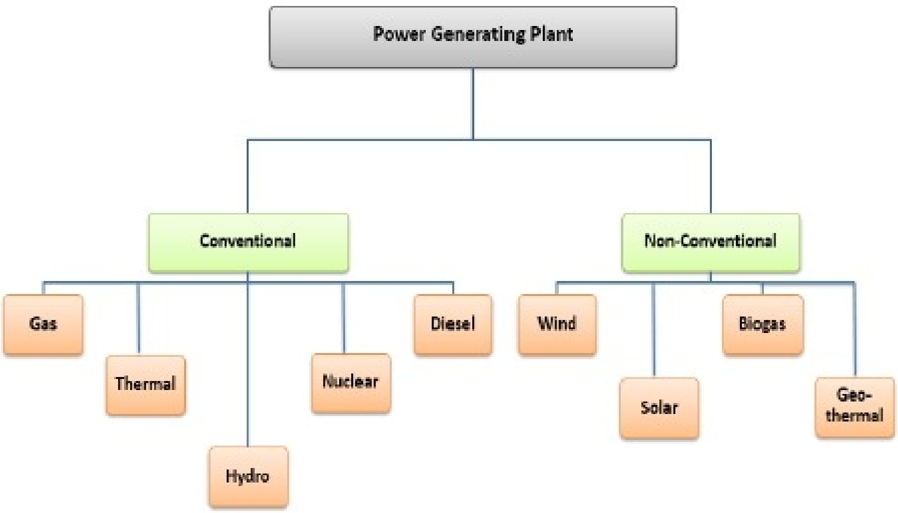

Figure 2.1 Classification of power generating plant.

Renewable energy or non-conventional energy sources do not emit greenhouse gases or pollutants into the environment which implies a lower carbon footprint. In paper [3] the author analysed that many of the emissions originates from carbon released as carbon dioxide when fossil fuels are burning. In other words, the fossil fuels emit excessive amounts of greenhouse gases that results in an increase in global temperatures and the frequency of extreme weather events. Therefore, the usage of renewable energy plays an important role in decreasing these pollutants.

In general, the power generating plant functions to convert mechanical energy into electrical energy using generators to produce electricity. Primarily, in generator, the shaft power generated by the prime mover is used to drive a generator that converts mechanical power rotation into electrical power [2]. The prime mover is a machine that convert primary energy from the power plant system to mechanical energy. To give an example, with aid of steam turbines, a steam power plant produces power. In the meantime, a gas turbine generator uses gas turbine as the prime mover to produce the electricity. This turbine or also known as turbomachines produces shaft power to convert kinetic energy, the mechanical work into shaft rotation. The principle block of the power system studied in this paper is as shown in Figure 2.2 [4].

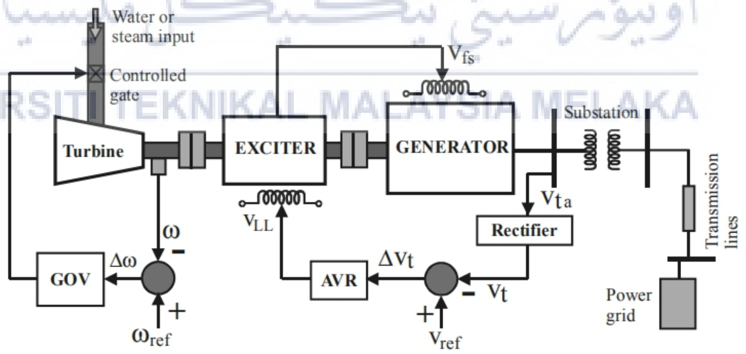

Figure 2.2 Control block diagram of power system. Adapted from [İsmail H. Altaş & and Jelle Neyens

Based on Figure 2.2, Load Frequency Control (LFC) plays a major role in a power plant. Thorough observations by author in paper [4] shown that changes in real power mainly affect the system frequency, while changes in reactive power is less sensitive to the frequency and it is mainly depending to the change in voltage magnitude. Thus, LFC functions in controlling the real power and the frequency of a system.

2.3 Classification of Power System Stability

Stability means the tendency of a power system to produce restoring forces equal to or greater than the disturbing forces to maintain the state of equilibrium [1][5]. Power system stability can be defined as the ability of a power system to remain in a synchronism in a normal operating condition and after the occurrence of disturbance in the system [6][7]. It can be classified as depicted in Figure 2.3.

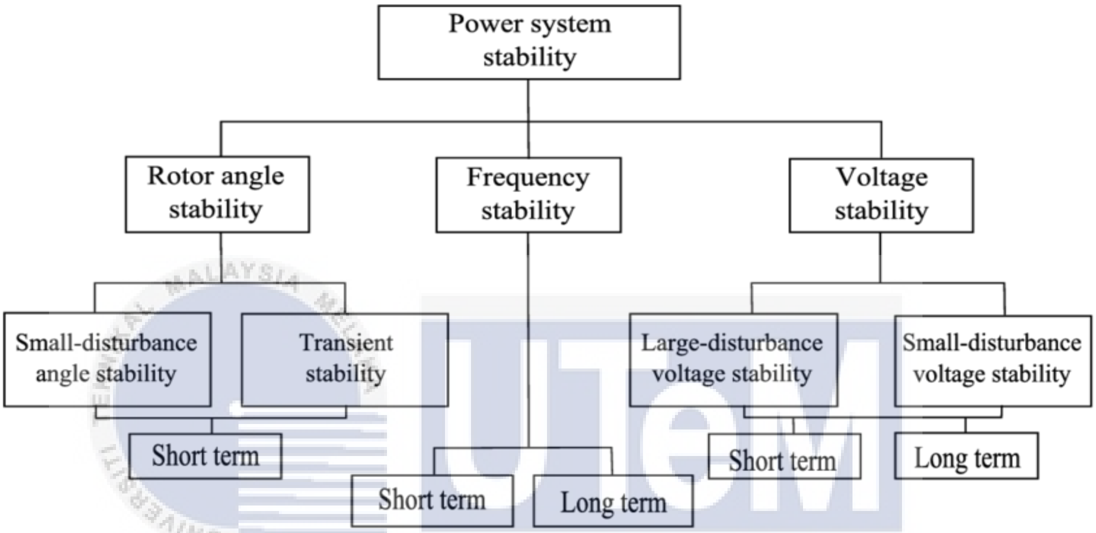

Figure 2.3 Types of power system stability phenomena. Adapted from [Kundur and Morisson, 1997a]

Many synchronous generators of the same frequency and phase sequence as generators are attached to the bus in power plants. The bus must be synchronized with the generators during the whole duration of generation and transmission to get a stable operation. The factor needs to be considered to get the synchronism is the stability of the system, mainly the rotor angle stability, frequency stability and voltage stability.

2.3.1 Rotor Angle Stability

Rotor angle stability control is the ability to adjust active power and reactive power of the interconnected synchronous machines that is running so that it remains in the synchronism state. According to author in paper [8], the rotor angle of a synchronous generator is normally controlled by both the active and reactive power modulation.

This is due to the existing of angular separation between rotor magnetic field and stator magnetic field. Rotor angle or also known as load angle definition is indicated in Figure 2.4.

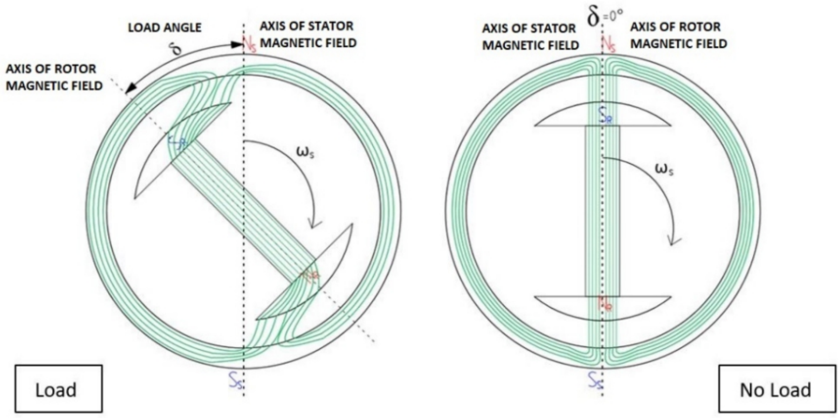

Figure 2.4 Rotor angle in synchronous generator

This angular separation appears to depend on the electrical torque or output power of the generator. The initial active power condition of the generator can then be determined for single machine infinite bus with the following equation (2.1).

$$P_g = \frac{V_t V_{bus}}{Z} \sin \theta \tag{2.1}$$

Where V_t is terminal bus voltage and V_{bus} is the infinite bus voltage. Swing equation will be applied for further calculation on analyzing the rotor angle stability.

2.3.2 Frequency Stability

Changes in frequency affects the stability of synchronous generator. This is because, frequency stability refers to a system's ability in maintaining steady frequency between generation and load. Basically, prime mover act as initiator to drive the rotor of synchronous generator. The speed of this rotor mainly affects the frequency of terminal voltage of the generator. To let generators to operate in synchronism, when two or more synchronous generators are connected, stator voltage and current of each generator must have the same frequency [9].

2.3.3 Voltage Stability

The main driving force that always led to voltage instability is usually the loads. Referring to the definition of voltage stability as proposed by IEEE task force, voltage stability is an ability of power system to keep voltages on every bus in steady state after some disturbances including an increase in load demand or changes in system state from a given starting operation point which may results in an uncontrollable and continuous drop of system voltage. When a normal operating condition is perturbed, the voltage angles of the synchronous devices can be changed. If such a condition causes an imbalance between the generation and the load, the subsequent adjustment of voltage angles generates new steady-state operating situation [5].

2.4 Power System Stability

Depending upon the nature of disturbance, the power system stability is classified into three types which are steady state, dynamical and transient stability.

2.4.1 Steady State Stability

The steady-state stability refers to the control system's ability to stay balanced and reverts to its original state when small disturbances occur [1][5]. In steady-state stability, a system can regain its synchronism after small and slow disturbance. Gradual power changes are one of the examples of steady-state stability. The stability behaviour can be analysed and defined in a linear system by analysing the system's characteristic equation [1]. The system to be considered is the single machine connected to an infinite bus bar.

2.4.2 Dynamical Stability

Dynamic stability relates to the small disturbances lasting for a long time with the inclusion of automatic control devices which then producing oscillations. The system is dynamically stable if the oscillations are of successively smaller amplitudes. In comparison, the system is considered dynamically unstable if the oscillations grow in amplitude [10].