COMPARATIVE STUDY OF THE EXCITATION SYSTEM, AVR AND PSS MODELS FOR SYNCHRONOUS GENERATORS UNDER THE PHASE TO GROUND FAULT

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SALIH M. EL SHARIF ABDALLA

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I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name: SALIH M. EL SHARIF ABDALLA

Signature:

Date:

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ÖZET

Bu tezin temel hedefi geçici rejim durumunda senkron jeneratör tahrik sistemlerinin, otomatik gerilim regulatörü (AVR) ve güç sistemleri stabilizörü (PSS) nğn davranışını incelemektir. Öncelikle geçici rejim stabilitesi teorisiyle ilgili dönüşüm denklemleri, transfer reaktansı, güç açısı grafiği ve kritik geçiş tamanı irdelenmiştir.

Tezde geçici rejim stabilitesi için çözüm dönüşüm eğrileri ve diferansiyel cebir denklemleri metodları kullanılarak aranmıştır. POWER-WORLD yazilimi bu konunun incelenmesi için kullanılmıştır. Çok üreteçli dokuz baralı bir sistem POWER-WORLD simulasyonu ile irdelenmiştir. Bu durumda bir çok geçici rejim durumu irdelenmiştir ve hepsinde arıza literatürde stabilite için gerekli olan 0.1 saniyede giderilmiştir. Tezin amacı olan AVR ve PSS tahrik sistemleri irdelenmiş ve röle ayarları için gerekli çeşitli güç parametrelerinin belirlenmesinde yardımcı olacak bir çalışma gerçekleştirilmiştir.

Anahtar kelimeler: Automatic Voltage Regulator (AVR), excitation systems, Power System Stabilizer (PSS)

ABSTRACT

In this thesis, the performance monitoring of synchronous generator excitation system, automatic voltage regulator (AVR) and power system stabilizer (PSS) under transient stability is the main purpose. Initially, the theory concerning to transient-stability and the transfer reactance, swing Equation, power angle curve and the critical clearing time has been discussed.

In this thesis, possible methods of transient stability have been studied with the solution for swing curve and differential-algebraic Equations method. The POWER-WORLD software is used to study the transient stability issues by using this method.

A POWER-WORLD simulation has been carried out to testify the performance of the multi-machine nine-bus system. For the method, the transient studies are tested in multi cases. For all cases, the fault cleared at time t = 0.1 second. In study of previous researched, proved that the system is stable at this period, The object of this research is to study performance of the excitation system, AVR and PSS. The program is helpful in determining voltage limit of systems and transfer energy between systems, critical power angle and critical clearing times for circuit-breakers. So, a better relay setting can be proposed.

Keywords: Automatic Voltage Regulator (AVR), excitation systems, Power System Stabilizer (PSS)

With love to my wife and all my family who have been always with me . . .

TABLE OF CONTENTS

CHAPTER 3: RESPONSE SYSTEMS

CHAPTER 4: RESULTS AND DISCUSSIONS

CHAPTER 5: CONCLUSION

LIST OF TABLES

LIST OF FIGURES

LIST OF USED SYMBOLS

θ :	The angular position of the rotor in rad.
δ :	The angular position in rad.
ω_r :	Angular speed of the rotor.
ω_s :	Synchronous speed in rad/s.
D :	Damping coefficient (pu)
Ef :	Field voltage V.
Efd :	Output field voltage from field-generator V.
ER :	Output voltage of the voltage regulator amplifier.
G(s), G(t) :	The low-pass filter transfer function.
GEP(s) :	Transfer function of the stabilizer output.
H :	Inertia constant.
If :	Field current A.
J :	The total moment of inertia of the rotor mass in kgm2.
KA :	Gain of the voltage regulator amplifier.
Mm Mc :	Mechanical torque and electromagnetic torque.
P :	Active power MW.
Pa :	Accelerating power in MW.
Pe :	Electrical power MW
PID :	Proportional integral derivative.
Pm :	Mechanical power MW.
Pmax :	V1V2/X is the maximum power can be transmitted over the line.
Q :	Reactive power MVAR.
Ta	Accelerating torque.
TA,TE,KE,SE:	Parameters of The exciter.
Td' :	The d-axis transient short-circuit time constant s.
Td'' :	The d-axis subtransient short-circuit time constant s.
$Td0'$:	The d-axis transient open-loop time constant s.
$Td0''$:	The d-axis subtransient open-loop time constant s.
Te :	The electrical torque output of the alternator in N-m.
Tm :	The mechanical torque supplied by the prime mover in N-m.
Tq'' :	The q-axis subtransient short-circuit time constant s.
$Tq0''$:	The q-axis subtransient open-loop time constant s.
Vf :	Voltage at the faulted**.**
VREF :	Reference voltage, voltage regulator V.
Vs :	PSS voltage.
Xd, Xq :	The d-,q-axis synchronous reactance (pu)
Xd', Xq' :	The d-,q-axis transient reactance (pu)

LIST OF USED ABBREVIATIONS

AVR :	Automatic voltage regulator.
BE :	Brushless exciter.
CCT :	The critical clearing time.
EX :	Excitation systems.
FCL :	Field current limiting.
FCT :	Fault clearing time.
IEEE :	Institute of Electrical and Electronic Engineers.
MX :	Main exciter.
OEL :	Over excitation limiter.
PSS :	Power system stabilizer.
PU :	Per unit.
SC :	Short circuit.
SG :	Synchronous generator.
UEL :	Under excitation limiter.

CHAPTER 1

INTRODUCTION

1.1 Introduction

In this study, power system stabilizer (PSS) and automatic voltage regulator (AVR) were studied to ameliorate the transient stability of generator in power system. The design problem of AVR and PSS were studied, and their performances were tested. The complex torque coefficient is observed by the time domain simulation. The test signal method is chosen for this purpose. The studied system consists of a multi-machine with slack bus system. Two types of excitation systems, AVR IEEE AC1A, ST1A excitation systems, and two types of PSS1A Power System Stabilizer, PSS2A Power System Stabilizer are chosen. The impacts of excitation systems with high response on the electrical damping are inspected. Six cases, the excitation system without PSS and with PSS are considered. At the same time, different input signals of PSS are used. The impacts of the parameters of PSS on the electrical damping are also studied.

The transient stability (large signal) stability problems have been studied such as phase to ground fault in power systems and which produced studies in many literatures power system is influenced by high electromechanical oscillations while a disturbance happens, which may cause to loss of synchronism of generators. High performance excitation systems are substantial to keep steady state and transient stability of generators and provide fast control and supported of terminal voltage. The generator excitation system using an AVR keeps the terminal voltage magnitude of a synchronous generator to a acceptable level. Also the excitation system and AVR provide to control the reactive power (Q) and get better stability. The AVR assists improving the steady-state stability of power systems. In transient state, machine is affected by disturbed impacts, especially in a short time that causes clear drop on the terminal voltage of machine.

The controller to raise damping of electromechanical oscillations is well-known as PSS. They are used to compensate the negative damping of AVR. Likewise, PSS is controlled the input signal of excitation system to damp out rotor oscillations.

1.2 Literature Review

Transient stability analysis issues have been widely discussed in the literature. Many parts of the stability problem have been covered with a lot of researches. Some of the researchers have covered the analytical study of the power stability problems. Others have focused on the methods of treatment and their effects on the stability. The discussion focuses on issues such as rotor angle stability, frequency stability and voltage stability. Other researches were looking for if the system is stable or unstable with a large disturbance such as a fault occurring (Wvong, 1989). In other researches, focus on a new robust control methodology to improve the power system transient stability. While others discussed the structure and comparison between performance of different devices to improve the stability.

Many programs of stability analysis use simple step by step integration methods to solve power system stability. While these methods have been applied for a long time, they can still be used to types of models. They are well known and accepted by the system operators. This allows easy analysis of the simulation in practice was discussed in (Grainger and Stevenson, 1994).

The voltage of the power system generator could be very low during a large disturbance such as a fault occurring on the generator bus, or in transmission lines near the generator, was reported by (Anderson and Fouad, 1997). During the fault, the flow of the electrical power to the power system is interrupted, and the generator rotor speed is risen by the input mechanical power. After the protection circuit breaker has cleared the fault, the generator is re-healthy to the power system and recapture the power supply to the system. Usually, the results of post-fault oscillations caused by the energy stored in the generator rotor during the cycles of the fault. The damper windings on the generator rotors can be used to control the oscillation, but this style is very costly. Compared with damper windings, the generator excitation control provides a better effective in cost and control. The idea simply that the generator excitation control that regulates the terminal voltage of the generator based on the terminal voltage feedback by the AVR. The AVR simply increases the field voltage to quickly recover the terminal voltage to the normal situation level. Such a quick recovery of the generator terminal voltage will force a negative effect on the damping of the post-fault oscillation. The power system stabilizer (PSS) as a extra controller to the AVR and generator excitation control, was reported in (Liu et al., 2007), if suitable designed, could remove any negative effects on the damping of the post-fault oscillation. Also was discussed and reported in (Kundur, 1994). Effect of a maximum value of over excitation limiter during the fault, possible provided to the system, was discussed in (Mummert, 1999).

In (Yeu, 2010) the small signal analysis of power systems are investigated by the power control system is such as excitation system, AVR, PSS and governing system. In (Loen, 2014) many block was discussed. The mathematical models for excitation system automatic voltage regulator (AVR), power system stabilizer (PSS). And study Performance analysis of various control devices. In (Saadat, 1999), the different methods to study the power flow solution steps of the stability systems studies.

In (Sumina et al., 2011) the power system stabilizer (PSS) is used in synchronous generator excitation control system for damping electromechanical oscillations. The goal of the PSS is to generate a stabilizing signal. And also the effects of different types of excitation systems and PSS was studied in (Zhang and Xu, 2007). The output of the main exciter is a nonlinear function of the inputs and which are related through the constant parameter, was discussed in (Bhaskar et al., 2000). The most practical obtainable method of transient stability analysis is time-domain simulation with the nonlinear differential Equations. In (Bose, 1984), the critical clearing time is the limit time for which a power system is allowed to stay in fault condition without losing stability. The accuracy and reliability of power system by limiting impacts of faults on the power system that the breaker clearing times should be corresponded with the normal critical clearing times. Suitable CCT settings of covering the power system determine the reliability and stability of power supply. Many papers have been discussed the transient stability analysis program used the method integration method has been presented in (Gafari, 2013). Numerical simulation of stochastic differential algebraic Equations for power system transient stability was discussed in (Wang and Crow, 2011).

Some others papers and researches have been written and discussed in the field of transient stability analysis. The subject of the power stability is a wide and very important.

1.3 Thesis Overview

The following is an outline of this thesis.

Chapter 1: Introduction to models of power systems, and a literature review discusses published information in a transient stability analysis.

Chapter 2: Review of the issues, the stability problem, and rotor angle stability, frequency stability and voltage stability of power system, the single phase earth fault in high voltage distribution networks that are low impedance ground.

Chapter 3: Review of the issues, the need for generator excitation control, the automatic voltage regulator AVR with or without power system stabilizer PSS, the design modern control excitation in power system. This chapter presents the excitation system, and turbine governor system for the design of an excitation control in this thesis.

Chapter 4: Simulations and results of the study for system analysis under single phase fault using analysis simulation with power-world version 18 simulation.

Chapter 5: The conclusion of this thesis.

CHAPTER 2

POWER SYSTEM STABILITY

2.1 The Stability Problem

The stability problem was discussed, the power-angle relationship, swing Equation are preface to our study. Then, the different parameters for which the analysis is offered include the fault clearing time (FCT), damping coefficient, generator armature resistance and fault location.

The single phase fault is mostly seen in networks, for this reason, in this thesis the single phase earth fault in high voltage transmission lines that are low impedance grounded is used. First, the basic of low impedance grounded system are discussed. The clearing time of earth faults, and the fault location are discussed and effect were observed.

The stable of power system means that all its multi-generators are operating in synchronism with the grid and with each other. The problems occur when the generators is oscillated by disturbances that occur by transmission faults. There are two types of stability problem in power systems. Firstly, the steady-state stability problem which mention to the stability of power systems when a small disturbance happens in the power systems such as a change in demands, manual or automatic changes in excitation system (Kundur, 1994).

Clearly, these small disturbances cannot cause loss of synchronism unless the system is operating at procedure action, its steady state stability limit (Kundur, 1994). This limit is the greatest power that could be transmitted in operating conditions in the steady state, without loss of synchronism. The analysis of steady state stability need to referenced at considerations of the solution of power flow Equations and swing Equations over a time of a few minutes. Exciters and governor should also be included in the steady state stability analysis (Saadat, 1999). Secondly, the transient stability problem that is occurred by a large disturbance in the power system such as an unexpected loss of generators or loads, circuit breaker close-open operations under large loads, or faults with circuit isolation. Such large disturbances make a power without equilibrium between generation and loads in the network. This unbalance appear at the generator shafts and causes the rotors to oscillate until a new stability operating point is appeared, or until the rotors continue to oscillate and deviate from each other and in the end some generators will lose synchronism.

Loss of synchronism should be stopped or controlled because it has a troubling effect on voltages, frequency and power, and it may cause dangerous damage to generators, which are the most costly factors in power systems (Grainger and Stevenson, 1994). The generators which tend to lose synchronism should be tripped and get out from the system before any harm occurs, and then comeback to synchronism. In this case, can be done easily with gas and water turbine generators, steam turbine generators need many long time to rebuild steam and in this case, the operator has to shed loads to compensate for the loss of generators, was discussed in (Anderson and Fouad, 1997). Loss of synchronism may also cause some protection relays to trip the circuit breakers of lines. The problem becomes very difficult and may result in more generators pulling out of synchronism.

2.1.1 Rotor Angle Stability

The rotor angle stability is known as the ability of multi- synchronous machines to keep in synchronism under normal operating conditions and after being attacked by a disturbance. Practically, the total active electrical power is given by the generators should be equal to the active power (p) used by the demands, this contains also the losses in the network. This equilibrium between the demand and generation can be correlating to the balance between the generator input, or mechanical torque, and the generator output, or electrical torque. A disturbance via system can annoyed this balance, that results in the acceleration or deceleration of the rotors of the generators. If one of generators suddenly runs faster than another, the angular position of its rotor close to that of the slower unit will increase. The outcome angular difference transfers a some of the load from the slow generator to the fast generator, depending on the power angle relationship, we will discuss next. This resort to reduce the speed difference and the angular deviation. Any more increase in angular deviation results in a decrease in power transfer, which can cause to instability (Agatep, 2013).

2.1.2 Frequency Stability

Frequency stability known as the ability of a power system to protect steady frequency. It depends on the ability to keep or carry back balance between power system generation and demand, with minimum loss of load. A idealistic cause for frequency instability is the loss of generation causing the all system frequency to drop. The frequency stability problems are connected with insufficiency in devices responses, harmony of control and protection devices, or generation control devices.

2.1.3 Voltage Stability

Voltage stability is a part of general power system stability. It denote to the ability of a power system to keep steady voltages at all bus bars in the system after being attacked by a disturbance. The voltage stability according to (Padiyar, 2008), a power system with operating point is small disturbance voltage stable if, after a small disturbance, voltages near demands are comparable to pre disturbance values. A power system at a given operating point and matter to a given disturbance is voltage stable if voltages near loads draw near post disturbance balance values. voltage collapse if post-disturbance balance voltages are below acceptable levels. Voltage collapse may be system large or ordinary. The major factor causing to voltage instability is usually the voltage drop that occurs when active and reactive power flow via inductive reactance's connected with the transmission line grid, as the line currents during different power flow conditions increase, the reactive losses raise. When reactive losses raise, the voltage magnitude decreases. And, as the active power flow increases the voltage magnitudes going to decrease. The system can no longer backup the active power flow on the lines and keep a stable voltage. So, the voltage collapses.

2.2 Effect of Power-Angle

In this thesis, the power-angle relationship are discussed. we will suppose this relationship for a parameter as one body. Principally, consider the one-machine infinite bus bar system shown in Figure 2.1. The reactance of system (x) is the total of the reactance of the synchronous reactance (X_d, X_q) or the transient reactance of the generator (X_d', X_q') and the power transmission line.

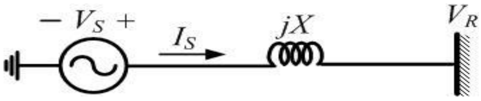

Figure 2.1: One system.

$$V_S = V_1\angle\delta, \quad V_R = V_2\angle 0° \tag{2.1}$$

$$I_S = \frac{V_1\angle\delta - V_2}{jX} = \frac{V_1\cos\delta - V_2 + jV_1\sin\delta}{jX} \tag{2.2}$$

The active power and reactive powers are given as

$$P_S + jQ_S = V_S I_S^* = V_1(\cos\delta + j\sin\delta)\frac{V_1\cos\delta - V_2 - jV_1\sin\delta}{-jX} \tag{2.2}$$

It will be

$$P_S + jQ_S = \frac{V_1V_2\sin\delta + j\left(V_1^2 - V_1V_2\cos\delta\right)}{X} \tag{2.3}$$

The total active power loss in line is very few, so the active power from the send-side is equal to the active power at the receive-side.

$$P_e = P_S = P_R = \frac{V_1V_2}{X}\sin\delta = P_{\max}\sin\delta \tag{2.4}$$

The power angle curve in Figure. 2.2. is shows that the input power(P_0). There are two values of the angle δ , (δ_0 and δ_{max}). The angles are:

$$\delta_0 = \sin^{-1}\left(\frac{P_0}{P_{\max}}\right) \tag{2.5}$$
$$\delta_{\max} = 180° - \delta_0$$

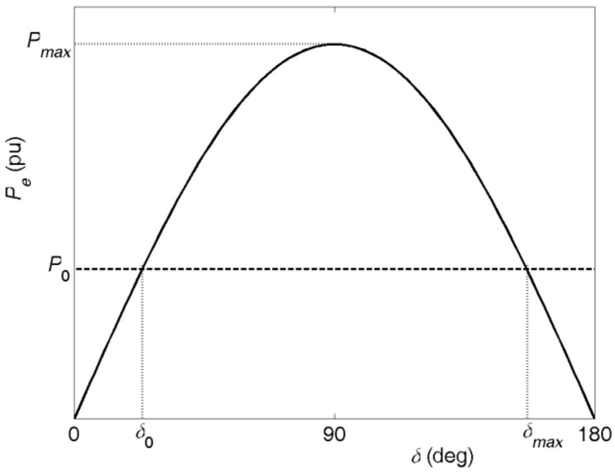

Figure 2.2: The power-angle curve

2.3 Swing Equation

The synchronous generator is driven by a turbine. Therefore, the Equation motion of the machine rotor is given by

$$J\frac{d^2\theta}{dt^2} = T_m - T_e = T_a \tag{2.6}$$

When the losses are ignored, the difference between the electrical and mechanical torque is known as accelerating torque (T_a). In the steady state, the electrical torque is equal to the mechanical torque, for this reason, the accelerating power will be zero. During this time, the rotor will shift at synchronous speed ω_s according to (Saadat, 1999).

The angular position θ belongs to a stationary reference scope. To represent it with respect to the synchronously rotating scope, it becomes:

$$\theta = \omega_s t + \delta \tag{2.7}$$

The time derivative of the last Equation, is:

$$\frac{d\theta}{dt} = \omega_s + \frac{d\delta}{dt} \tag{2.8}$$

The angular speed of the rotor as: $\omega_r = \dfrac{d\theta}{dt}$

We can re-write (2.8) as

$$\omega_r - \omega_s = \frac{d\delta}{dt} \tag{2.9}$$

The rotor angular speed is equal to the synchronous speed only when dδ/dt is equal to zero. where dδ/dt is the error in speed. The derivative of (2.8), we can re-write as

$$J\frac{d^2\delta}{dt^2} = T_m - T_e = T_a \tag{2.10}$$

Multiplying both side of (2.10) by ω_m

$$J\omega_r \frac{d^2\delta}{dt^2} = P_m - P_e = P_a \tag{2.11}$$

The inertia constant as:

$$H = \frac{\text{Stored kinetic energy at synchronous speed in mega - joules}}{\text{Generator MVA rating}} = \frac{J\omega_s^2}{2S_{rated}} \tag{2.12}$$

Changing (2.12) in (2.10) then,

$$2H\frac{S_{rated}}{\omega_s^2}\omega_r \frac{d^2\delta}{dt^2} = P_m - P_e = P_a \tag{2.13}$$

In steady state, the angular speed of machine is equal to the synchronous speed and we can replace ω_r in the last Equation by ω_s. In (2.13) P_m, P_e and P_a are offered in MW, so dividing both sides by the generator MVA rating S_{rated}, then the quantities in per unit.(2.13).

$$\frac{2H}{\omega_s}\frac{d^2\delta}{dt^2} = P_m - P_e = P_a \quad \text{per unit} \tag{2.14}$$

2.4 Multi-Machine Transient Stability

For transient stability, for guess the critical clearing time is significant. When a system fault happens, the fault should be cleared before the system can under unstable. In a multi-machine generator system under a transient, every generator can oscillate, and the difficulty of calculating the system performance during a transient increases with the multi -generators (Grainger and Stevenson, 1994).

The simple way for the analysis of a multi- generators power system for transient stability studies, we have the following steps that were discussed in and (Anderson and Fouad, 1997).

- During the transient, the machine power for all generators is constant.
- Damping power is ignored.
- Every generator is modeled as a fixed transient reactance in series with a fixed internal voltage.
- The angle of each internal voltage is equal to the rotor angle of every generator.
- Each load is modeled as a constant reactance, equal to its pre-fault value.
- Machines belonging to the same station(brothers-machines) swing together and are well-knit. A group of coherent machines is represented by one equivalent machine (Gafari et al., 2013).

And for transient stability analysis has the following steps: (Saadat, 1999).

1. Before the system occur fault, solve the load flow Equations to determine the initial value.
2. The way followed the network model before fault, decide the system during fault and for the post-fault case.
3. Solve the swing Equations and calibrate if the system is stable or unstable.

.

In power system under transient stability and through the system we looking for point to Improving power system stability includes the next cases:

- Increasing capacity of transmission lines with multi-line during pre-fault conditions.
- Quick fault clearance, promote transient stability limits.
- Fast circuit breaker re-close, increases transmission system capacity in the post-fault state and improve transient stability.

- Increased mechanical inertia of generators, decreases angular acceleration, slows down rotor angle oscillations, and so increases CCT.

2.5 The Swing Equations For Multi Machine System

Directly, the equal area criterion with the multi machine system cannot be used in power systems where multi generators are synchronized. It was discussed in (Grainger and Stevenson,1994). The calculation of (Y) matrix for each grid condition as pre fault, during and after fault. The numbers (n) of generators, the nodal Equation can be written as:

$$\begin{bmatrix} I_n \\ 0 \end{bmatrix} = \begin{bmatrix} Y_{nn} & Y_{nr} \\ Y_{rn} & Y_{rr} \end{bmatrix} \begin{bmatrix} V_n \\ V_r \end{bmatrix} \tag{2.15}$$

The n used to denote generator nodes and the r is used for the remaining nodes. The Equation (2.15), will be

$$I_n = Y_{nn} V_n + Y_{nr} V_r \tag{2.16}$$

$$0 = Y_{rn} V_n + Y_{rr} V_r \tag{2.17}$$

$$I_n = \left(Y_{nn} - Y_{nr} \; V_{rr}{}^{-1} + Y_{rn} \right) V_n \tag{2.18}$$

Then can be written as

$$Y_R = (Y_{nn} - Y_{nr} \; V_{rr}{}^{-1} + Y_{rn}) \tag{2.19}$$

For the power system during study, the reduced matrices are calculated. Appendix D show the results matrices before, during and after fault. The power into the grid at node i, that is the electrical power output of unit i, is given by (Anderson and Fouad, 1997).

$$P_{ei} = E_i \, G_{ii} + \sum_{\substack{n=1 \\ n \neq 1}}^{n} E_i E_j Y_{ij} \cos\left(\theta_{ij} - \delta_i + \delta_j\right) \quad i = 1,2,3 \; \dots . n \tag{2.20}$$

Where ,

$$\overline{Y}_{ij} = Y_{ij} \, \theta_{ij} = G_{ij} + JB_{ij} \tag{2.21}$$

Negative of the admittance between nodes i and j

$$\overline{Y}_{ii} = Y_{ii} \, \theta_i = G_{ii} + JB_{ii} \tag{2.22}$$

The Equations of motion are

$$\frac{2H_i}{wR}\ \frac{d\omega_j}{dt} + D_i\ \omega_j = P_{mi} - \left[E_i^{\ 2}\ G_{ii} + \sum_{\substack{n=1 \\ n\neq 1}}^{n} E_i E_j Y_{ij} \cos\left(\theta_{ij} - \delta_i + \delta_j\right) \right] \qquad (2.23)$$

$$\frac{\mathbf{d\delta i}}{dt} = w_i - w_R \qquad i{=}1.2.3$$

$$P_{mi\,0} = E_i^{\ 2}\ G_{ii0} + \sum_{\substack{n=1 \\ n\neq 1}}^{n} E_i E_j\ Y_{ij0} \cos\left(\theta_{ij0} - \delta_{i0} + \delta_{j0}\right) \quad i = 1,2,3\ \ldots .\,n \qquad (2.24)$$

The 0 here is used to point out the pre-transient conditions. As the network is changed by circuit breaker during the fault, and The critical clearing time (CCT) is

$$t_{cr} = \sqrt{\frac{4\,H}{w_s\,P_m}(\delta_{\,cr} - \delta_{\,0})} \qquad (2.25)$$

In this thesis, we have considered three machines, and to analysis if the system stable or unstable. The rotor angles for machines are:

$$\delta_{\,21} = \delta_{\,2} - \delta_{\,1} \qquad (2.26)$$

$$\delta_{\,31} = \delta_{\,3} - \delta_{\,1} \qquad (2.27)$$

2.6 Single-Line-To-Ground Fault

The sequence networks and the sequence circuits, the steps for calculating the fault current under unsymmetrical faults. For the computation of fault currents, we need the following cases, it was discussed (Grainger and Stevenson, 1994). The cases:

1. Before the fault the power system is balanced, only the positive sequence network is active. When the fault applies, the sequence networks are connected only through the fault location.
2. The fault current is ignored such that the before fault positive sequence voltages are same at all nodes and at the fault location.

3. All the grid line charging capacitances and resistances are negligible.
4. All loads are passive except the rotating loads (motors) that are represented by synchronous machines.

The faulted network as shown in Figure. 2.3 where the voltage at the faulted area will be known by V_f and current in the three faulted phases are I_{fa}, I_{fb} and I_{fc}. We will research how the three sequence networks are connected under the single phase fault condition.

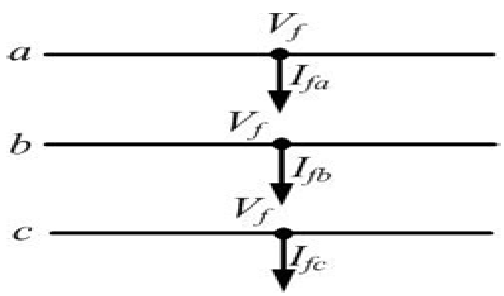

Figure 2.3: Single-line-to-ground fault

The single phase fault has occurred at point (k) of a grid. shown in Figure. 2.4 where it is supposed that phase-a has contact the ground via an impedance Zf. In this thesis we suppose that the fault impedance is low. Since the system is unloaded before the occurrence of the fault, we have

$$If_B = If_C = 0 \tag{2.28}$$

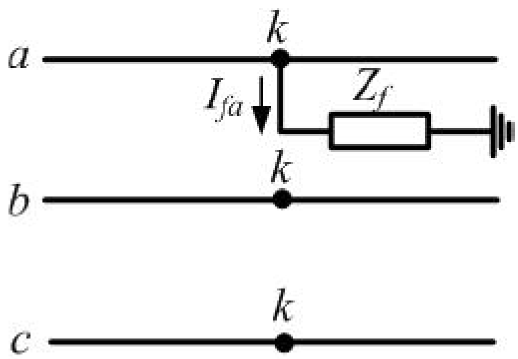

Figure 2.4: Single phase fault

The phase-a voltage at the fault is

$$V_{ka} = Z_f \; I_{fa} \tag{2.29}$$

$$I_{fa} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} I_{fa} \\ 0 \\ 0 \end{bmatrix} \tag{2.30}$$

$$I_{fa0} = I_{fa1} = I_{fa2} = \frac{I_{fa}}{3} \tag{2.31}$$

For the single phase fault the three sequence currents are in series. To signify the zero, positive and negative sequence Thevenin impedance at the faulted area as Z_{kk0}, Z_{kk1} and Z_{kk2}. The voltage at the faulted phase is V_f, we have three sequence circuits that are the same shown in Figure 2.5 the Thevenin equivalent of the sequence network. So,

$$V_{ka0} = -Z_{kk0} \; I_{fa0} \tag{2.32}$$

$$V_{ka1} = V_f - Z_{kk1} \; I_{fa1} \tag{2.33}$$

$$V_{ka2} = -Z_{kk2} \; I_{fa2} \tag{2.34}$$

$$V_{ka} = Z_f \; I_{fa} = Z_f \left(I_{fa0} + I_{fa1} + I_{fa2} \right) = 3\,Zf \; I_{fa0} \tag{2.35}$$

$$I_{fa0} = \frac{Vf}{\left(Z_{kk0} + Z_{kk1} + Z_{kk2} + 3\,Zf \right)} \tag{2.36}$$

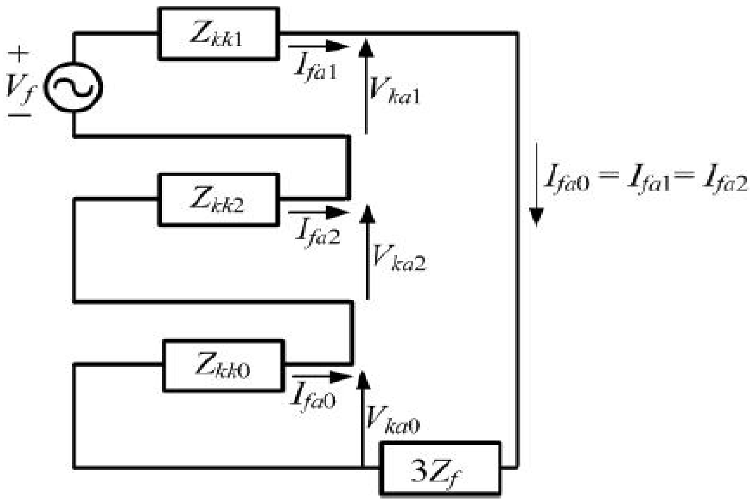

Figure 2.5: Thevenin equivalent of the sequence network

The analysis of synchronous generator by mathematical model is the basis for qualitative analysis of a synchronous generator and its system stability, which consist of the flux Equation and voltage Equation, and the rotor motion Equation indicating the torque and rotor speed change (Ying and Jian, 2013). Its six order mathematical model is as follows:

$$T_J \frac{d\omega}{dt} = M_m - M_c - D(\omega - \omega_0) \tag{2.37}$$

where,
TJ is Generator inertia constant

$$\frac{d\delta}{dt} = \omega - \omega_0 \tag{2.38}$$

For synchronous reactance, transient reactance and sub-transient

$$T'_{do} \frac{dE'_q}{dt} = dE_{fd} - (X_d - X'_d)I_d - E'_q \tag{2.39}$$

$$T''_{d0} \frac{dE''_q}{dt} = -E''_q - (X'_d - X''_d)I_d + E'_q + T''_{d0} \frac{dE'_q}{dt} \tag{2.40}$$

$$T'_{d0} \frac{dE'_q}{dt} = -E'_q + (X_d - X'_d)I_q \tag{2.41}$$

$$T''_{q0} \frac{dE''_d}{dt} = -E''_q - \left(X'_q - X''_q\right)I_q + E'_d + T''_{q0} \frac{dE'_d}{dt} \tag{2.42}$$

2.7 Transient Stability

The methods is used in Chapter 4 with power-world simulator.
A set of differential Equations:

$$dx/dt = f(x, y) \tag{2.43}$$

A set of algebraic Equations:

$$g(x, y) = 0 \tag{2.44}$$

X: variables are dynamic state variables and Y: variables are bus voltage and angle.

The solutions of the system by these Equations are to determine the electromechanical of the power system at any time (Wang et al., 2008). Equations (2.43) and (2.44) were solved by a partition solution method or a simultaneous solution method. In the partitioned solution method, the differential Equations are solved by a standard numerical integration method with algebraic Equation (2.44) being solved one by one during time step, was discussed in (Martins and Lima, 1990). The simultaneous solution employs implicit integration methods to change the differential Equations of (2.43) into a set of algebraic Equations which are joint with the algebraic network Equations of (2.44) to be solved as one set of simultaneous algebraic Equations solutions (Gafari et al., 2013). Appendix E shows the program for the transient stability solution.

The basics of analysis systems to improve transient stability. We suppose a constant impedance load and that the system can take in constant power during a fault. We studied and considered the direct impact of the CCT for Single-line-to-ground fault, the power to the load during a fault and the trajectories of rotor angle (during pre-fault, fault, and post-fault) conditions.

CHAPTER 3

RESPONSE SYSTEMS

3.1 Response Systems

The power control system is such as excitation system model, automatic voltage regulator (AVR), power system stabilizer (PSS) and the governing system. The Study focuses on the mathematic models of AVR and PSS which can increase the stability of the generator. The Figure 3.1 shows the power control system structure.

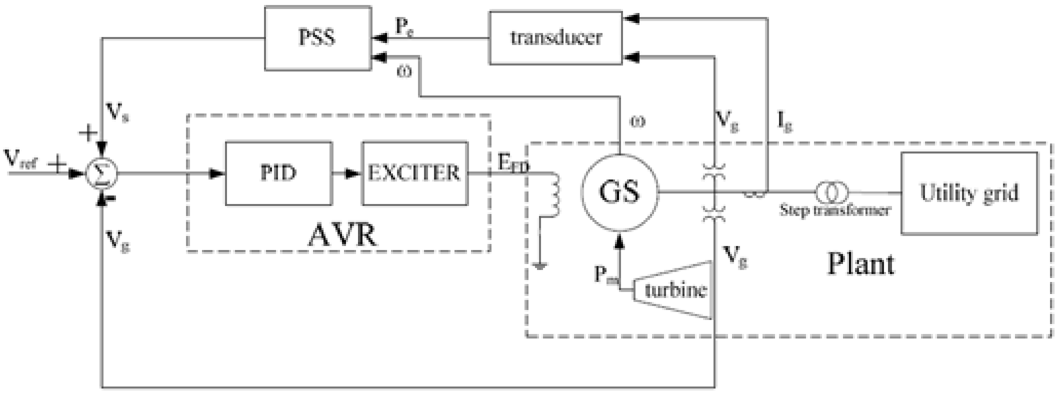

Figure 3.1: The system structure (Tang, 2011)

The power control system let the system go back to the case of stability. By the quick response to control the generator output voltage, and speed of unit and to increase the damping ratio to generator to increase the stability after disturbance. The power control system consists of unit, the AVR, and PSS.

3.2 Generation Control Systems

The generator receives the mechanical power (Pm) from the turbine or mover. The control signal to the rotor field voltage EFD generated by the AVR that regulates the magnetic field and to maintain the output voltage of the generator. The stator and the power network are connected by the step transformer to supply power to the network. The Figure 3.1 shows that there is one input and three outputs. The input is the control signal EFD from AVR output. The three outputs go to be feedback signal to the control system voltage output, current and rotor rotational speed (ω). The signals of voltage and current crosses the control system through the transducer and get out to PSS as the electrical power (Pe). The rotor speed ω and electrical power (Pe) are the input signal to the PSS to estimate the power change due to the possible rotor speed oscillation induced by oscillation disturbance from the power network. After oscillation is applied, PSS is expected to increase the damping ratio of the closed-loop system so as to damp out or reject the oscillation disturbance from the power network.

3.2.1 Governing System

The turbine governing system is the responsible of the power system which controls the input to the turbine to control the generator speed and the active power to response the demand. The turbine governing system lets the machine able to start up, reach its operational speed and operate with the required power output. The turbine governing system controls the mechanical input power (Fuel), so that the power input is reduced as the speed increases, before the synchronization, and control the mechanical torque after the synchronization. This way the balance between the input and output power is maintained. The types of governing system such as steam , gas and hydro turbines. In Chapter 4, simulations and results study focuses on hydro power plant. A functional diagram of a standard hydraulic turbine governing system is shown in Figure 3.2**.**

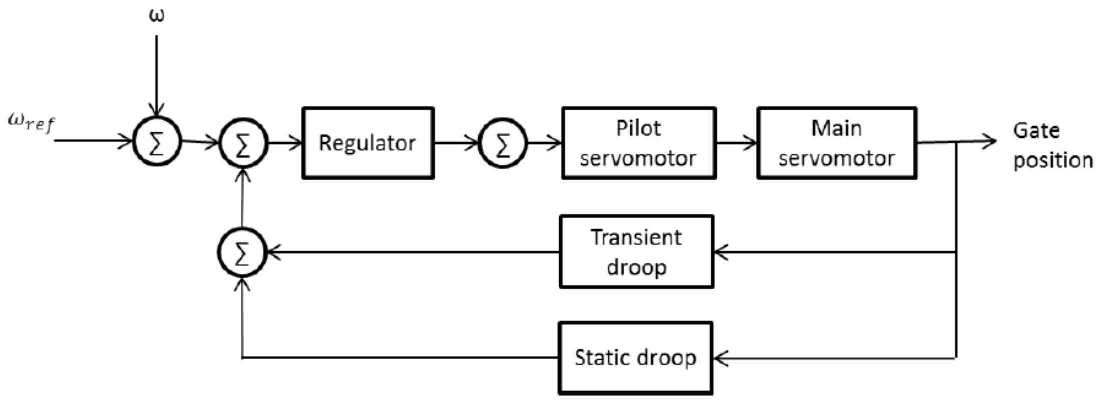

Figure 3.2: Block diagram of hydraulic turbine governing system.

The most important difference between the hydro turbine governing system and the gas, steam turbine governing systems, is that a higher power is wanted to reset the control gate, as the water pressure and the frictional forces are high. In Figure 3.2 the feedback loop with the transient droop, allows the water flow to control the changes in the gate position (Loen,2014). Turbine governing system model is considered in Chapter 5 as simulations and results.

3.2.2 Exciters

There are three types of exciters, DC exciters, AC exciters and static exciters, and in this thesis we focused in AC exciters type ACA1 and static exciters type STA1.

3.2.2.1 AC Exciters (Brushless)

In Figure 3.3 AC exciter is three phase synchronous generators, consisting of a rotating armature and stator field.

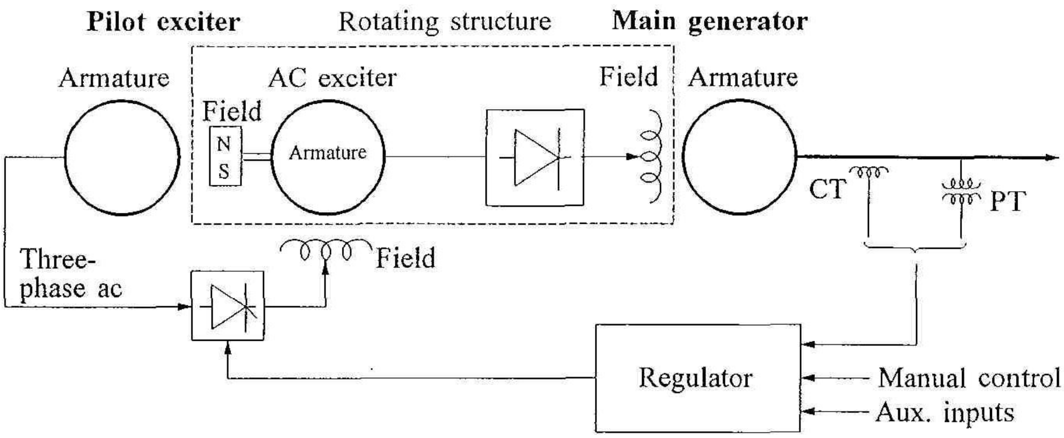

Figure 3.3: A.C. Exciter (Kundur, 1994)

The output is rectified by solid-state rectifier located on the same unit on the shaft rotating and the output go directly to fed of the machine's field winding. The stator field winding of the AC exciter is controlled from the AVR. AC exciter model is suitable for power system stability studies (Taborda, 2010). The specifications of AC exciter by the following:

1. No brushes in the exciter.
2. Work together of a single machine on the unit with the same shaft.
3. Medium time response in Vf, as only one transient time constant delays the response, the static power converter delay is small in comparison.

3.2.2.2 Static Exciters (Brushed)

This type of exciter is controlled by rectifiers directly supplying the field winding of the SG via brushes.

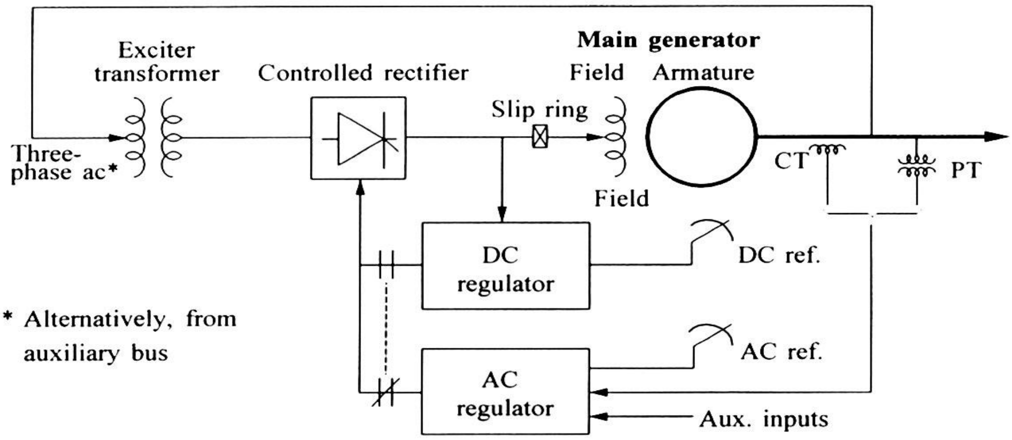

Figure 3.4: Static Exciter (Kundur, 1994)

The controlled rectifier is supplied from a power transformer connected that is feeding from network. Static power electronics exciters are fast voltage response, but still the time constant of the SG delays the field current response. Figure 3.4 show system structure.

3.2.2.3 Over Excitation Limiter (OEL)

The limiter is used to set the level current into the SG field. A short fixed time delay is used to let the excitation system to supply maximum field voltage while induced currents flow during faults. Usually, at the beginning of operation and before connecting via system ,this limiter is lower point. Without time delay is used under those cases. This limiter usually uses lower set points when the machine is offline.

3.2.2.4 Under Excitation Limiter (UEL)

An under excitation limiter (UEL) is used to limit the levels of reactive current flowing into the generator. More specifically, protect the machine as work as motor. Generally this limiter has been used for of two aims. The first, the loss of field relay, to protect the machine from loss of synchronism with the power system. The second has been to protect the generator against overheat due to an extreme increase in under excited vars.

3.2. 3 Automatic Voltage Regulator (AVR)

The main purpose of the AVR is to control the output voltage (Vg), of the generator, with the control signal EFD or the rotor field. The AVR consists of the PID controller and exciter. The block diagram of the AVR is shown Figure 3.5.

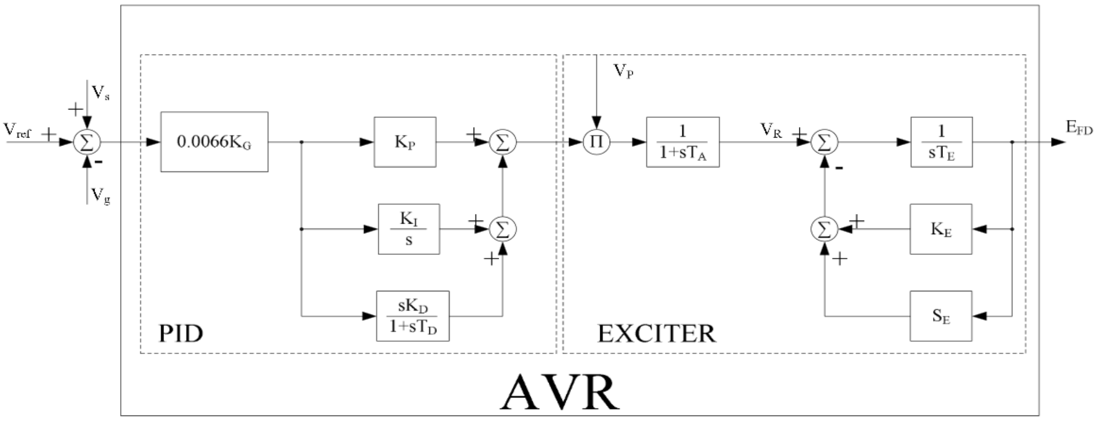

Figure 3.5: The block diagram of the AVR (Tang, 2011)

The Vg is feedback to the system, Vref is the set-point voltage, and Vs is the feedback from the PSS. The output EFD is the voltage across the rotor winding that induces the magnetic field so as to control the output voltage (Vg), of the generator. The exciter side with Vp the constant power source voltage that is controlled with the PID output voltage to increase the voltage EFD high enough to create the rotor's magnetic field. The result of the PID output and Vp has to be low pass filtered to clear any noises to being used as the control signal. The parameters of the exciter TA, KE, TE and SE, the ideal value TA= 0, and all other parameters is different from station to another station which cannot be changed. The signal model for AVR in Laplace domain is:

$$EFD = 0.0069KG.VP.G_{EXC}(S).\left(KP + \frac{KI}{S} + \frac{SKD}{1 + \mathrm{TD}}\right).(\mathrm{V_{REF}} + \mathrm{VS} - \mathrm{Vg}) \tag{3.1}$$

Vp serves as an amplification gain, K_G loop gain of AVR.

$$G_{EXC}(S) = \frac{1}{STE + KE + SE} \tag{3.2}$$

G_{EXC} is the transfer function of the exciter that depends on the body of the exciter and can be changed in traditions. When PSS is not installed, Vs = 0. In this case, the AVR regulates only the output voltage Vg. When PSS is installed, AVR needs to help to increase the damping ratio of the close loop system (Muriithi and Nyakoe, 2015).

3.2. 3.1 Type AC1A Excitation System Model

It belongs to the AC exciters family. The block shown in Figure 3.6 the field-controlled alternator-rectifier excitation systems type AC1A. This excitation system have an alternator main exciter (MX) with non-controlled rectifiers. The voltage regulator power is supplied from a source that is not influenced by outer transients. The diode in the exciter output force a lower limit of zero on the exciter output voltage.

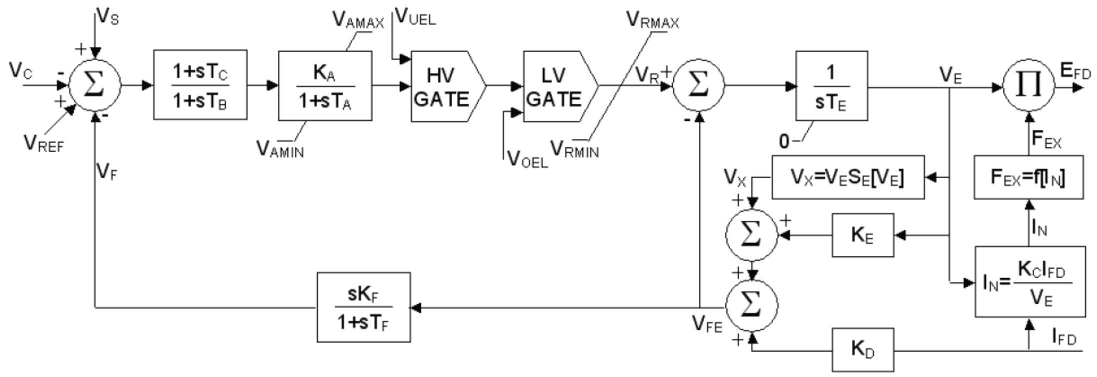

Figure 3.6: Type AC1A excitation system model

For large power system stability studies, the excitation system of generator can be explained by the simplified block shown in Figure 3.6. The demagnetizing effect of load current IFD, on the excitation output voltage VE, is passed as a feedback channel that includes the constant KD. This constant is a function of the exciter alternator synchronous and transient reactance (IEEE Standard 421.5, 2005, 2006). The Exciter output voltage drop is simulated by both of the constant KC and the rectifier regulation curve FEX. Data in Appendix B.

3.2. 3.2 Type ST1A Excitation System Model

The type ST1A power-source controlled-rectifier excitation system shown in Figure 3.7 is designed to represent systems that the excitation power is supplied via a power transformer. This transformer on line with the same network, and is regulated by a controlled rectifier (IEEE Standard 421.5, 2005, 2006). The exciter time constants are very small, and exciter stabilization may not be needed. Successfully, it may be eligible to make smaller the transient gain of these systems for other reasons. The block shown is multilateral to represent transient gain reduction performed either in the forward channel through time constants, TB and TC (in normal KF = 0), or in the feedback channel by compatible choice of rate feedback parameters, KF and TF. Voltage regulator gain and any excitation system time constant are given by KA and TA. The time constants, TC1 and TB, allow for the chance of transient gain increase, always TC1 should be greater than TB1. The firing angle for the bridge rectifiers is took affects the input-output relationship, that is supposed to be linear in the model by choice of a simple gain, KA. For plenty of systems a really linear relationship applies. In a some systems, the bridge relationship is not linear, leaving this nominally linear gain a sinusoidal function, the amplitude of that may be dependent on the voltage supply.

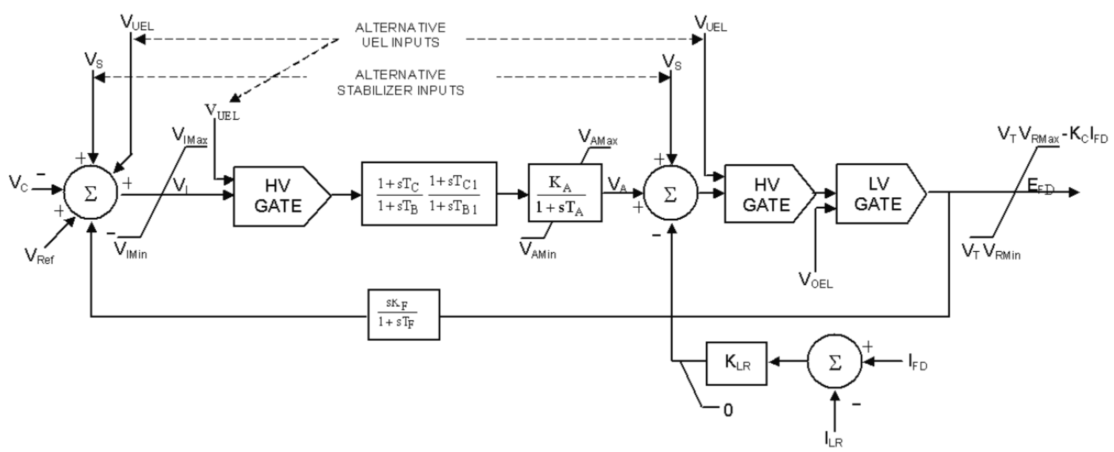

Figure 3.7: Type ST1A excitation system model (Pajuelo et al., 2010)

As the gain is usually set very high, sometimes the limits on VI can be ignored. The exemplification of the field voltage positive limit as a linear function of synchronous generator. The negative limit would have a similar current, the sign could be either positive or negative depending about whether a constant firing angle or constant extinction angle is selected for the limit. As field current is usually low under this condition. As a result of the high capability, a field current limiter is sometimes used to keep the generator rotor and exciter in safety level. The limit start setting is known by ILR and the gain is known by KLR. And have to be to allow KLR = 0. This limiter is illustrated here to keep unity with the original ST1A over-excitation and under-excitation limiters. In (Kawkabani et al.,2013). Usually, of these excitation systems, a completely controlled bridge is used, the model is also serviceable to systems with only half of the bridge is controlled, in this case the negative field voltage limit is set to zero (VRMIN = 0). Data in Appendix B.

3.2.4 Power System Stabilizer (PSS)

There are many oscillation are occurred in power systems and they usually are applied by the power network. There are three different oscillations occur in power generators and transmission networks. They are local mode oscillations (0.7-2Hz), inter unit oscillations (1-3Hz), and inter area oscillations about (0.5Hz). These frequency oscillations, maybe let the AVR to react and exporting the oscillation to rotor angle of the synchronous generator that may result in serious outcomes such as tripping the unit from the grid (Tang, 2011). Practically, the AVR without external support is not suitable to treat the oscillation. Perhaps the AVR can be a cause of the problem to rotor angle oscillation. Oftentimes rotor angle oscillation can be minimized by the damping torque. But if a enough damping torque is not occurred, the result can be increasing the rotor angle oscillation. the angle change rate of the rotor speed change $\Delta\omega$ overtop to 180°, the generator will lose the synchronism that will cause shutdown by protective equipment. The disturbance in the other system, due to the loss of generation, may cause units tripping. So, it is very important to raise the damping torque or damping ratio of the closed-loop system to minimize the rotor angle oscillation. The rotor angle oscillation is the result of rotor speed change. The IFD is the current in rotor winding and ΔIFD is the rate of change the current of the rotor field. The PSS is very important, that is try to reject the oscillation from the power network and to stop The effect at the rotor speed or angle. Because the signals of PSS and AVR are feedback controllers, it is important to confirm that they need to be designed together in order to optimize the power feedback control system and to complete the aim of damping out the rotor angle oscillation and the aim of voltage regulation with each other. The analysis of ΔIFD, the signal $\Delta\omega$ is necessary to the controller to increase the damping ratio of the closed-loop system. But in case, if AVR work without external support, $\Delta\omega$ cannot be feedback, because the signal of voltage Vg alone has not got any data of $\Delta\omega$. So the way here is to use PSS to guess $\Delta\omega$ and feedback it to minimize the oscillations of the rotor angle and lead Vs such as input signal to the AVR. As a result, by using PSS and AVR with each other, closed-loop system damping ratio can be increased and the rotor angle oscillation can be minimized. And in this thesis we focus on power based stabilizer.

3.2.4 .1 Type PSS1A Power System Stabilizer Model

Figure 3.8 shows the PSS with a single input. The common stabilizer input signals VSI are frequency, speed and power (IEEE Standard 421.5- 2005, 2006).

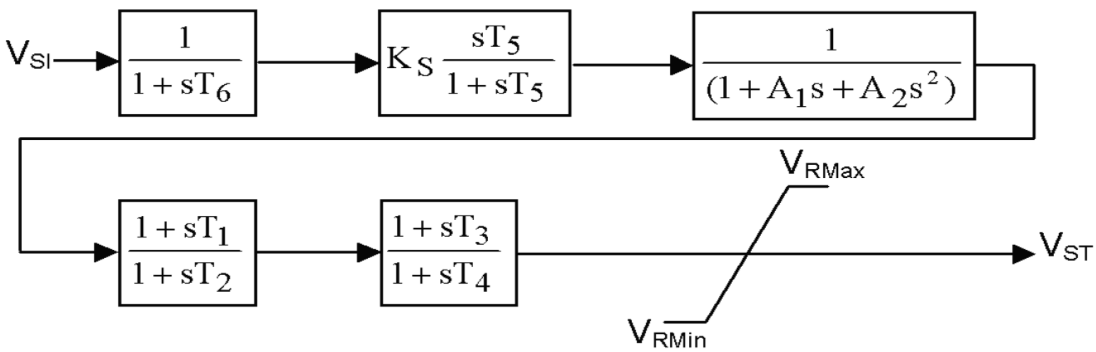

Figure 3.8: Type PSS1A power system stabilizer model

T6 be used to be a symbol for a transducer time constant. Stabilizer gain is KS. The signal washout is put by the time constant T5. The A1 and A2 let some of the low-frequency impacts of high-frequency filters. The next two models allow two periods of lead-lag compensation, as set by constants T1 to T4. Stabilizer output can be limited in different ways. This block shows simple stabilizer output limits, VSTMAX and VSTMIN. For some systems. The stabilizer output VST is an input to the additional control models. Data in Appendix B.

3.2.4 .2 Type PSS2A Power System Stabilizer Model

The minimization in other oscillation stabilizer designs have lead to the development of a stabilizer based on the integral of accelerating power (P_a). This type of stabilizer is IEEE standard well-known stabilizer PSS2A (IEEE Standard 421.5, 2005, 2006). The aim of compensating generator active power change to hold back an negative stabilizing signal from occurring in conditions. The primary analysis of stabilizer PSS2A merge electrical power with mechanical power, to get the integral of accelerating power. With speed and active power. The IEEE standard PSS2A block used for showing this stabilizer design in Figure 3.9. The fundamental of PSS2A stabilizer works with the synchronous machine motion Equation (3.3).

$$\Delta\omega = \frac{1}{T_m}\int(\Delta P_m - \Delta P_g)dt \tag{3.3}$$

$$\int \Delta P_m \, dt = T_m \Delta w(t) + \int \Delta P_g \, dt \tag{3.4}$$

The PSS2A stabilizer uses Equation (3.4) to receive a signal proportional to the mechanical power deviation integral by inserting signals proportional to speed deviation and the electrical active power deviation integral. As signal may have torsion modes and it is needful to involve a low-pass filter to clear oscillation torsion modes. The integral of accelerating power, when Equation (3.4) is added Equation (3.5), the integral of accelerating power is assigned to rotation speed deviation and generator active power deviation.

$$\frac{1}{Tm}\int \Delta P_a \, dt = G(t)\left[\Delta w(t) + \frac{1}{Tm}\int \Delta P_g \, dt\right] - \frac{1}{Tm}\int \Delta P_g \, dt \tag{3.5}$$

The *G*(t) is the low-pass filter transfer function. Equation (3.5), in the Laplace domain determines the compute of the integral of accelerating power using rotor speed and electrical active power values.

$$\frac{1}{Tm}\frac{\Delta P_a(s)}{s} = -\frac{1}{Tm}\frac{\Delta P_g(s)}{s} + G(s)\left[\frac{1}{Tm}\frac{\Delta P_g(s)}{s} + \Delta w(s)\right] \tag{3.6}$$

The *G*(s) is the low-pass filter transfer function. The case with *G*(s) =1, stabilizer PSS2A is equivalent to phase minimal stabilizer with a rotor speed input signal. During the case of *G*(s) = 0, the stabilizer PSS2A turn into an active power input stabilizer (Sumina et al., 2011). In spite of the fact that stabilizer PSS2A has a lot of benefit over a single input stabilizer, it is sensitive to the relations between rotor speed and active power. If the adjustments are to be favorable, two signal channel 1and 2 in Figure 3.9, should be tuned with estimate to gain and time constants of the filter. Active power signal channel 2, Figure 3.9 contains models for the derivation of electrical active power deviation integral (Sumina et al., 2011).

$$\frac{1}{T_m}\frac{\Delta P_g(s)}{s} = \left[\frac{sT_W}{1+sT_W}\right]\left[\frac{K_{s2}}{1+sT_7}\right]P_g \tag{3.7}$$

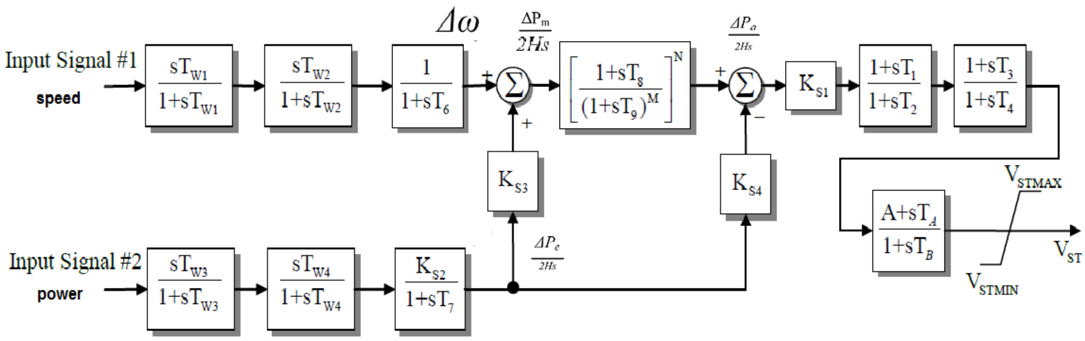

Figure 3.9: Type PSS2A power system stabilizer model (Lee et al., 2006).

The both signal $\Delta\omega$ the output from channel 1 and $\frac{\Delta P_e}{2H_S}$ the output from channel 2 are got together. then the result is $\frac{\Delta P_m}{2H_S}$ then this mixed signal passes the ramp filter, and the end result is the integral-of-accelerating power signal $\frac{\Delta P_a}{2H_S}$

The aims of this power control systems, is initially to keep the generator output voltage, stable at the set point. Secondly, is to minimize the rotor oscillation, to keep the generator output stable, by the automatic voltage regulator. And to minimize the rotor angle oscillation, we involve PSS to damping out the rotor angle oscillation and give reference signal Vs to AVR to raise closed-loop system damping ratio.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Power System Simulation And Models

The main target of this thesis is analysis study and the effect of the AC1A and ST1A excitation systems. Type PSS1A Power System Stabilizer, type PSS2A Power System Stabilizer are chosen, for transient stability analysis using the electrical power system design and analysis simulation power-world 18. The aim of performing transient stability on the power system is to study the stability of a system under disturbances (phase to ground fault with solid impedance).

In this Chapter, we have considered multi-machine, nine-bus system shown in Figure 4.1. This system was discussed in references (Nallagalva et al., 2012), and widely used in the literatures. The base MVA is 100, and system frequency is 60 Hz. The system data are given in Appendix A. The system has been simulated with a classical model for the generators. The disturbance here is the transient by a single-phase fault occurring at approximately in the middle of line 5–7. The fault is cleared by opening line 5–7 (Anderson and Fouad, 1997). Two types of excitation system models, AVR and PSS were compared and these models are shown in Table 4.1. Looking for the best response situation and health points. The fault in the system may be going to instability and the units will loses the synchronism. If the system can keep operation until the fault is cleared, then the all system will be in stable. Through the instability not only the swing in rotor angle for the final position continue increasing, but also the variation in angular speed. In such a case the system will not come to its final position. The unbalanced status or transient condition may go to instability where the units in the power system fall out of synchronism and may be all the system will black out.

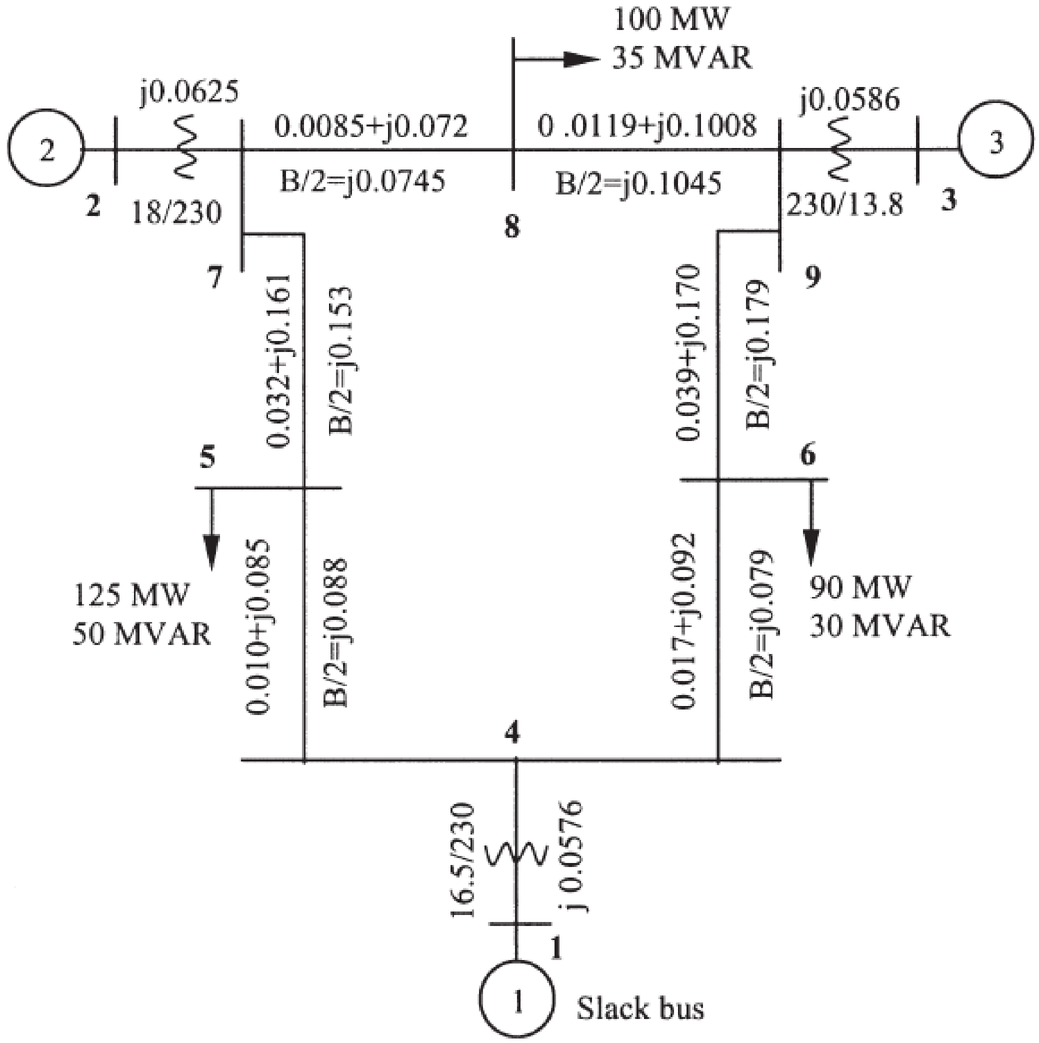

Figure 4. 1: Multi-machine, 9-bus system, all impedances are in pu -100MVA base

4.2 The Effect Of Fault Location And Fault Clearing Time

There are some important and influential factors in the study. For all cases, the fault location is 40% during tests were considered.

To analysis the impact of fault clearing time on transient stability, a disturbance in the form of a phase to ground fault was simulated. The critical clearing time, which is a criterion of the stability in power system, depends on the fault clearing times. The stability and instability of the power system at a given fault is decided by the actions of the generators in the system. If the rotor angles of the machines diverge, the system is unstable, and if otherwise the system is stable.

4.3 The Comparative Method

In this work, the differences between rotor speed, stator voltage output, rotor angle and excitation voltage output will be studied. The Table 4.1 will be followed step by step to analysis IEEE 9 Bus system using power-world simulator will be used.

.

Table 4.1: Excitation System Models, AVR and PSS

Case 1: Type ST1A excitation system model Type PSS1A Power System Stabilizer fault cleared at time, t = 0.1 second Fault Location 40 % between bus 5-7	**Case 2:** Type ST1A excitation system model Without Stabilizer fault cleared at time, t = 0.1 second Fault Location 40 % between bus 5-7
Case 3: Type ST1A excitation system model Type PSS2A Power System Stabilizer fault cleared at time, t = 0.1 second Fault Location 40 % between bus 5-7	General fault resistance = solid Governor IEEEG1 Cycles =240--246
Case 4: Type AC1A excitation system model Type PSS1A Power System Stabilizer fault cleared at time, t = 0.1 second Fault Location 40 % between bus 5-7	**Case 5:** Type AC1A excitation system model Without Stabilizer fault cleared at time, t = 0.1 second Fault Location 40 % between bus 5-7
Case 6: Type AC1A excitation system model Type PSS2A Power System Stabilizer fault cleared at time, t = 0.1 second Fault Location 40 % between bus 5-7	General fault resistance = solid Governor IEEEG1 Cycles =240--246

4.4 Power-World

The Y-matrix for each network condition (pre-fault, during and after fault) is calculated. In a power system with multi-generators, the nodal Equations in Chapter 2. Sequence data for all devices such as generators, transmission lines, transformers and loads.

1- Before Fault

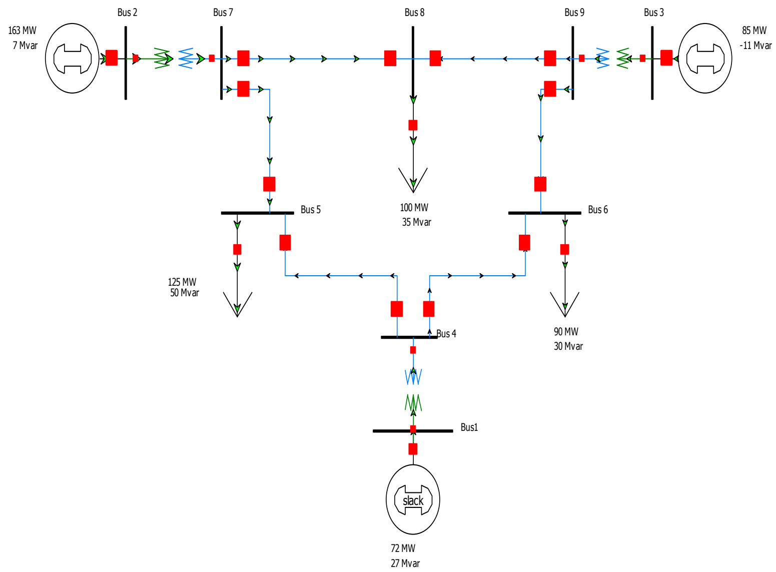

Figure 4. 2: Multi-machine, 9-bus system before-fault with POWER-WORLD

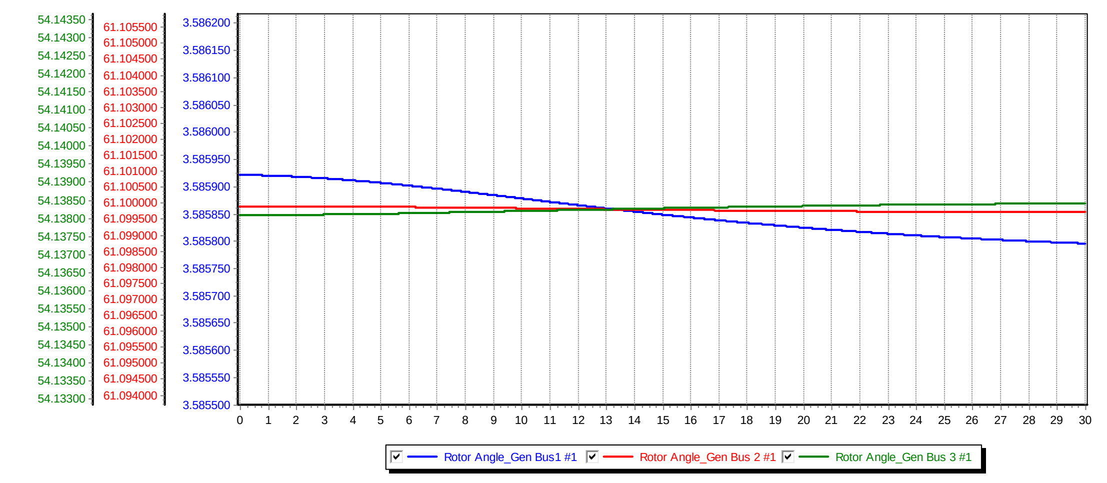

Figure 4.3: Rotor angle before fault

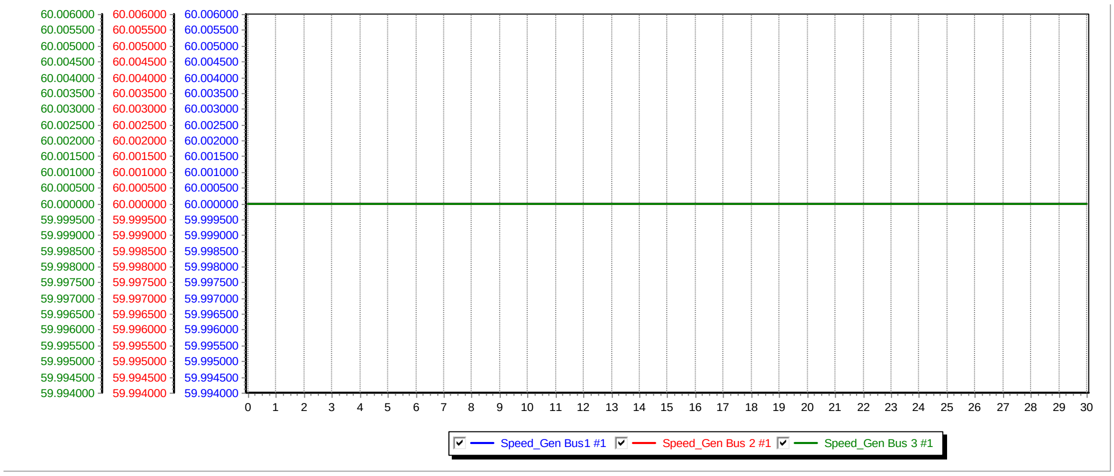

Figure 4.4: Speed before fault

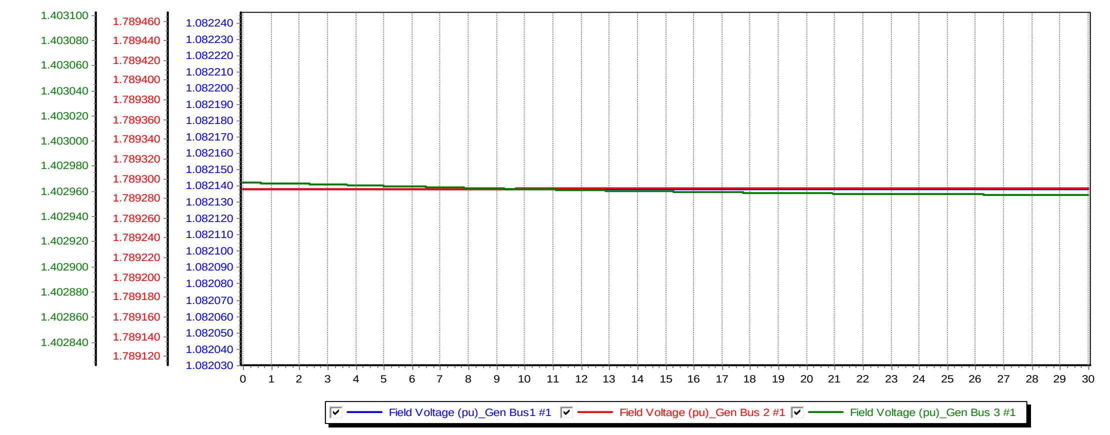

Figure 4.5: Excitation before fault

2- During Phase To Ground Fault Between Bus 5—7 Location 40%

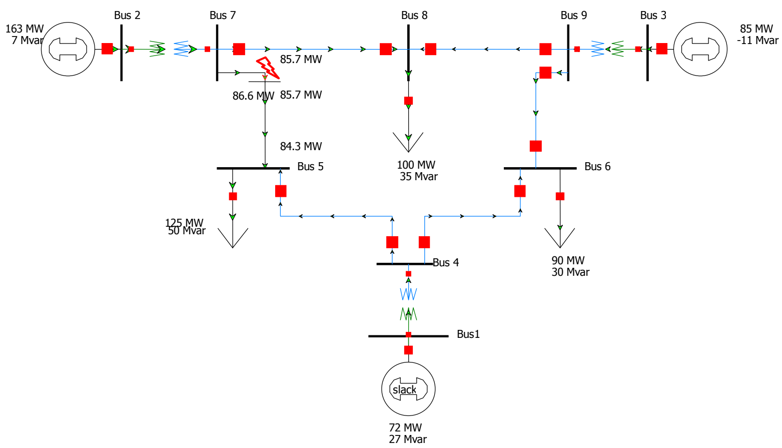

Figure 4.6: Multi-machine, 9-bus system during-fault With POWER-WORLD

3- After Fault Cleared

A phase to ground fault short circuit is added in the line 5-7. The fault happens at 4 second and the circuit breakers operate at 4.1 second, t = 0.1 s. The total simulation time is 30 seconds, time step is 0.008 s.

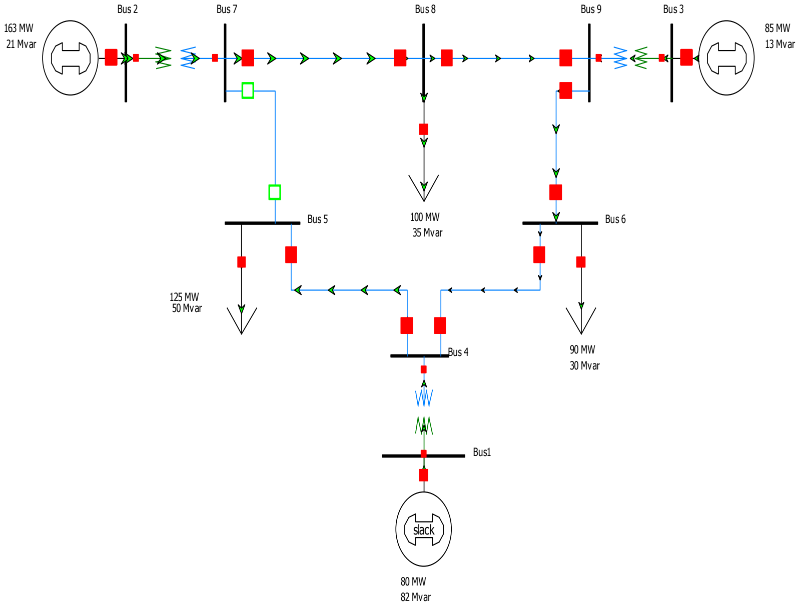

Figure 4.7: Multi-machine, 9-bus system after-fault With POWER-WORLD

Case 1:

- **Rotor speed**

Figure 4.8 show the rotor speed during the fault for Case 1. It can be seen in the plots that the highest oscillation are for unit 1 is 60.25 to 59.8 HZ, unit 2 is 60.3 to 59.7 HZ and unit 3 is 60.2 to 59.8 HZ. It takes approximately 10 seconds after the fault occurrence to return to steady state.

- **Stator voltage**

Figure 4. 11 show the stator voltage during the fault for Case 1, the voltage oscillation close for unit 1 from 1.09 to 0.97 pu , for unit 2 from 1.24 to 0.92 pu, and for unit 3 from 1.16 to 0.88 pu during the fault and it start to recover after the operation of the circuit breakers to clean the fault. approximately 10 seconds after the fault occurrence to return to steady state.

- **Rotor angle**

Figure 4.10 show the rotor angle during the fault for Case 1, the rotor angle oscillated close for unit 1 from 8° to -28°, for unit 2 from 86° to 58°, and for unit 3 from 59° to 49°.

- **Excitation**

Figure 4.9 show the stator voltage during the fault for Case 1, the support voltage for unit 1 from 1.6 to 0.65 pu, for unit 2 from 2.5 to 1.3 pu , and for unit 3 from 2.2 to 0.9pu return to steady state. approximately 10 seconds.

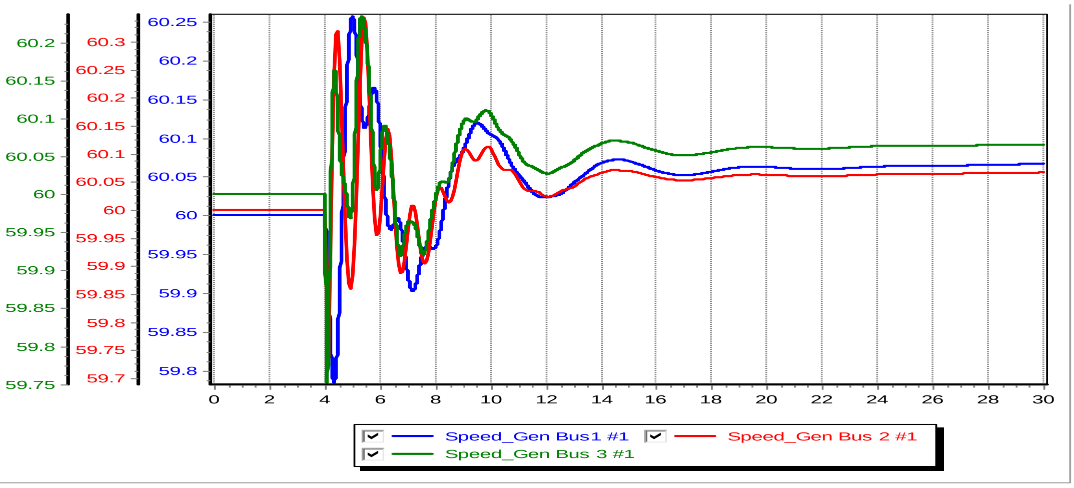

Figure 4.8: Case 1-ST1A with PSS1A

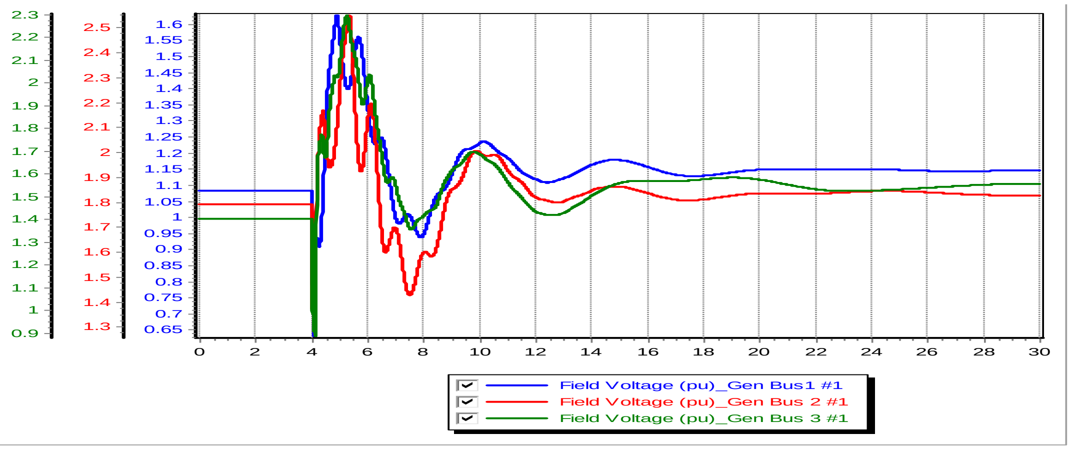

Figure 4.9: Case 1-ST1A with PSS1A

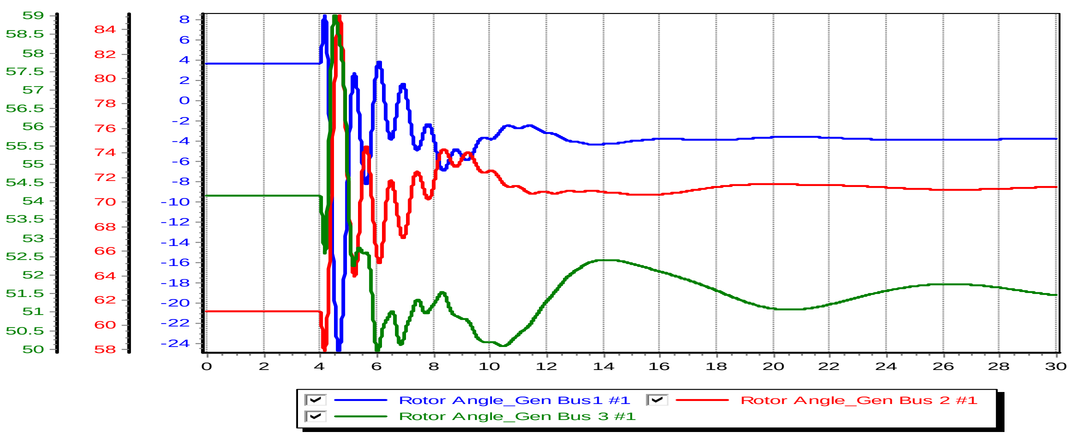

Figure 4.10: Case 1-ST1A with PSS1A

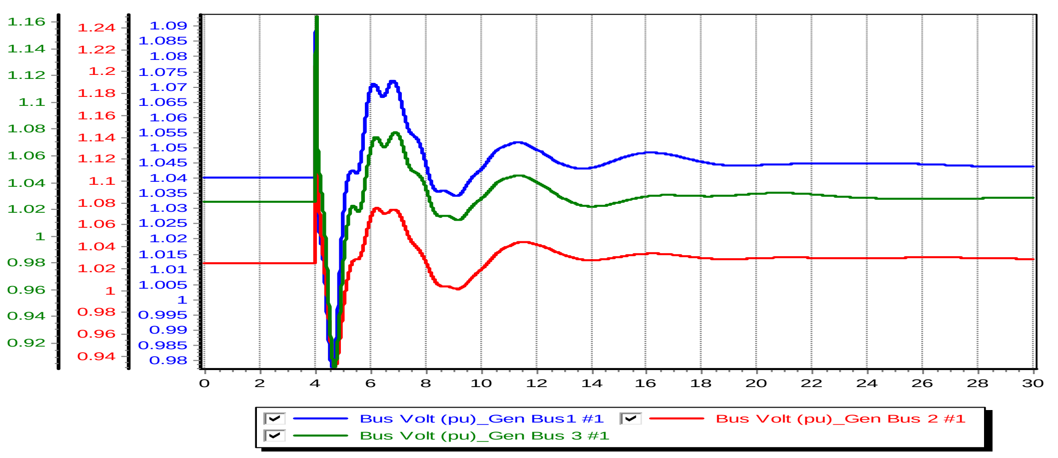

Figure 4.11: Case 1-ST1A with PSS1A

Case 2:

- **Rotor speed**

Figure 4.12 show the rotor speed during the fault for Case 2. It can be seen in the plots that the highest oscillation are for unit 1 is 60.25 to 59.8 HZ, unit 2 is 60.35 to 59.7 HZ and unit 3 is 60.25 to 59.8 HZ. It takes approximately 12 seconds after the fault occurrence to return to steady state.

- **Stator voltage**

Figure 4.15 show the stator voltage during the fault for Case 2, the voltage oscillation close for unit 1 from 1.09 to 0.985 pu, for unit 2 from 1.24 to 0.92 pu, and for unit 3 from 1.16 to 0.9 pu, during the fault and it start to recover after the operation of the circuit breakers to clean the fault. approximately 12 seconds after the fault occurrence to return to steady state.

- **Rotor angle**

Figure 4.14 show the rotor angle during the fault for Case 2, the rotor angle oscillated close for unit 1 from 8° to -26°, for unit 2 from 86° to 58°, and for unit 3 from 59° to 50.5°.

- **Excitation**

Figure 4.13 show the stator voltage during the fault for Case 2, the support voltage for unit 1 from 1.4 to 0.85 pu, for unit 2 from 2.25 to 1.3 pu, and for unit 3 from 2 to 1 pu return to steady state. approximately 10 seconds.

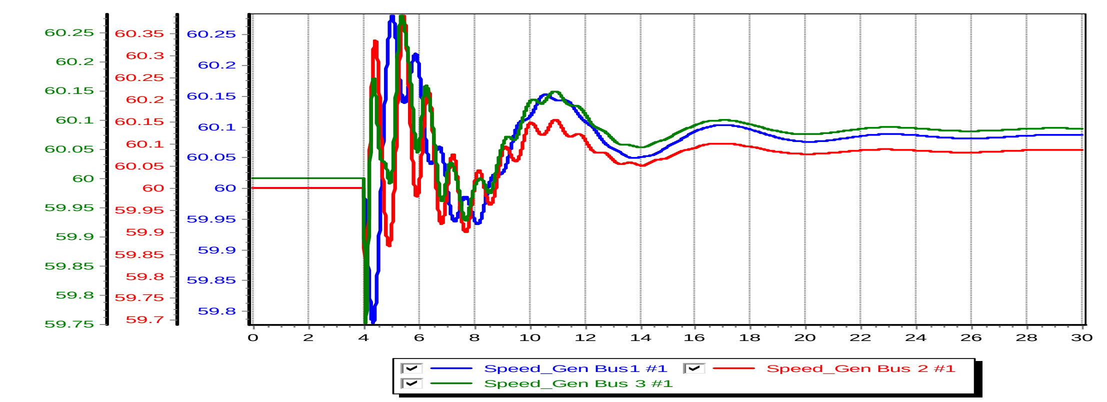

Figure 4.12: Case 2-ST1A without - PSS

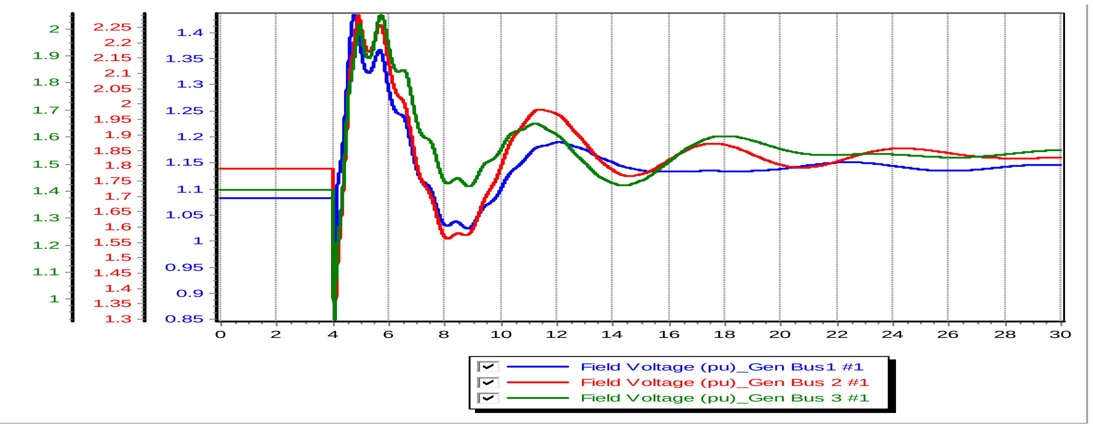

Figure 4.13: Case 2-ST1A without – PSS

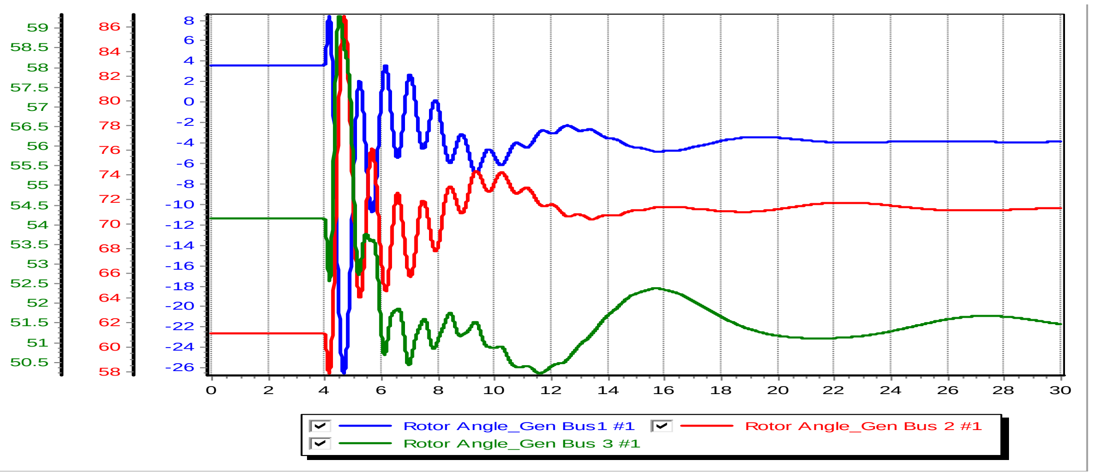

Figure 4.14: Case 2-ST1A without – PSS

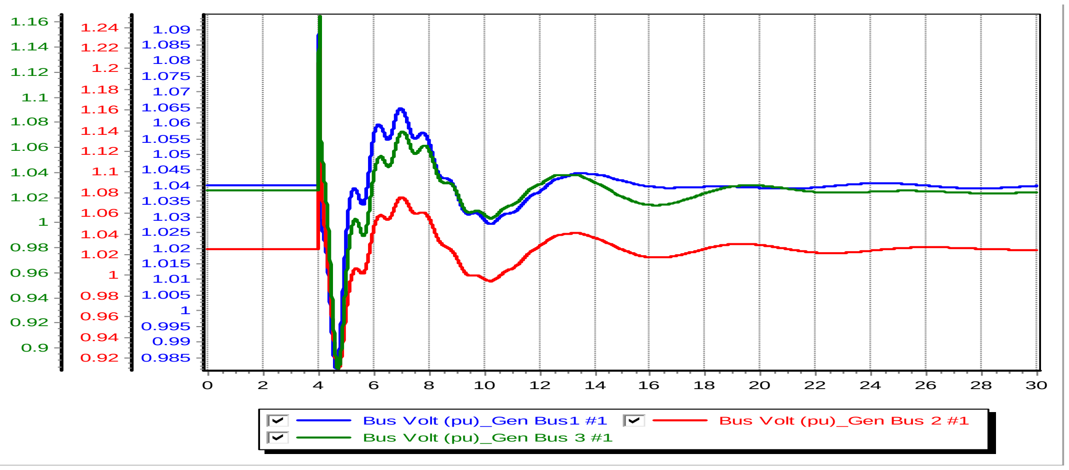

Figure 4.15: Case 2-ST1A without - PSS

Case 3:

- **Rotor speed**

Figure 4.16 show the rotor speed during the fault for Case 3. It can be seen in the plots that the highest oscillation are for unit 1 is 60.25 to 59.8 HZ, unit 2 is 60.35 to 59.7 HZ, and unit 3, 60.25 to 59.8 HZ. It takes approximately 12 seconds after the fault occurrence to return to steady state.

- **Stator voltage**

Figure 4.19 show the stator voltage during the fault for Case 3, the voltage oscillation close for unit 1 from 1.09 to 0.98 pu, for unit 2 from 1.24 to 0.94 pu, and for unit 3 from 1.16 to 0.9 pu during the fault and it start to recover after the operation of the circuit breakers to clean the fault. approximately 12 seconds after the fault occurrence to return to steady state.

- **Rotor angle**

Figure 4.18 show the rotor angle during the fault for Case 3, the rotor angle oscillated close for unit 1 from 8° to -24°, for unit 2 from 84° to 58°, and for unit 3 from 59° to 50°.

- **Excitation**

Figure 4.17 show the stator voltage during the fault for Case 3, the support voltage for unit 1 from 1.6 to 0.65 pu, for unit 2 from 2.4 to 1.3 pu, and for unit 3 from 2.1 to 1pu return to steady state. approximately 10 seconds.

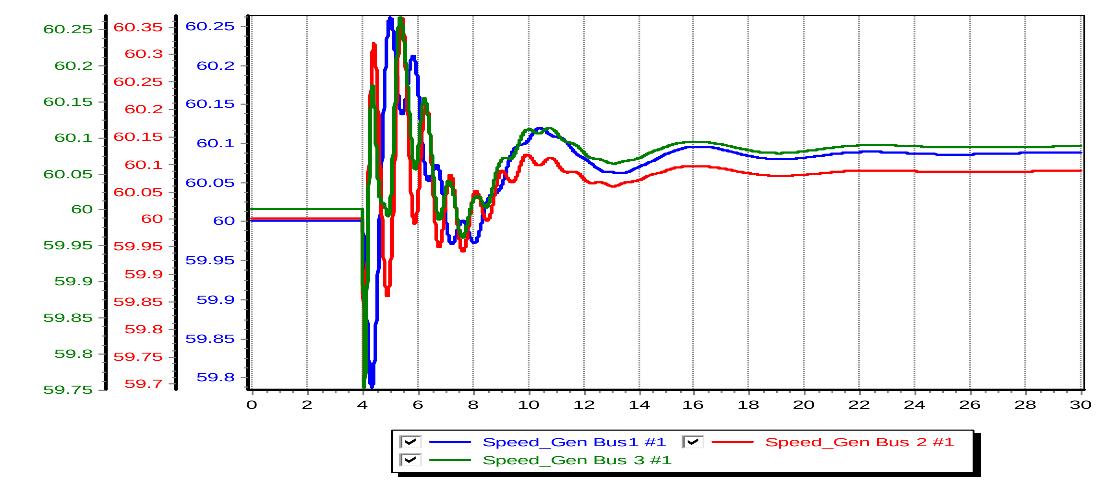

Figure 4.16: Case 3-ST1A with PSS2A

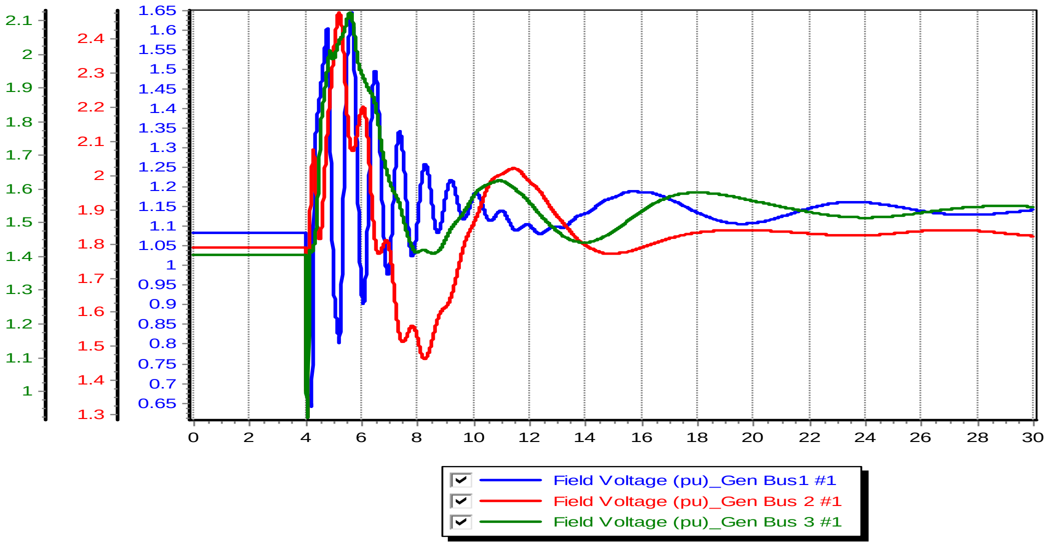

Figure 4.17: Case 3-ST1A with PSS2A

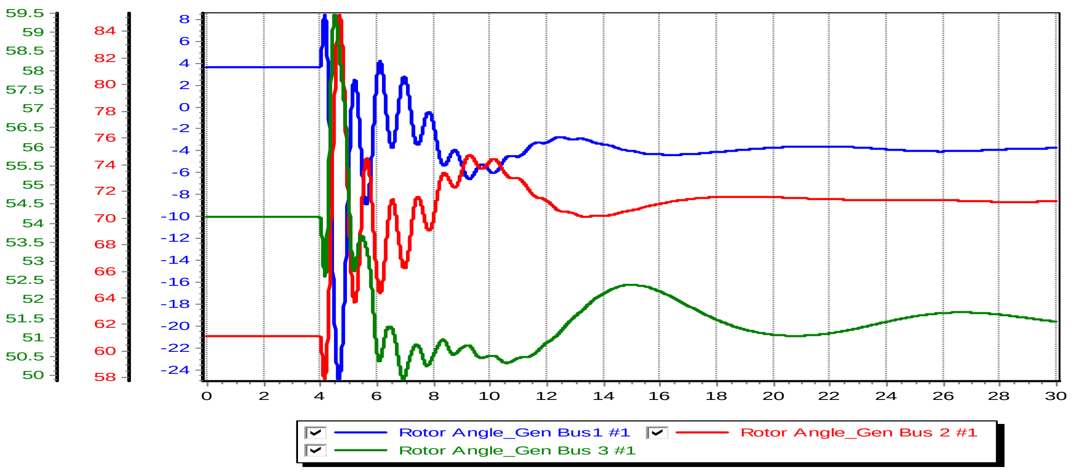

Figure 4.18: Case 3-ST1A with PSS2A

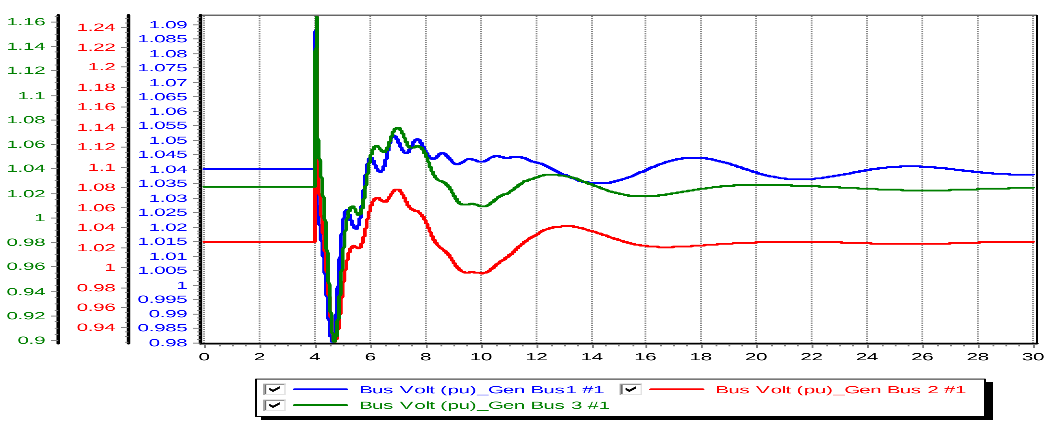

Figure 4.19: Case 3-ST1A with PSS2A

Case 4:

- **Rotor speed**

  Figure 4.20 show the rotor speed during the fault for Case 4. It can be seen in the plots that the highest oscillation are for unit 1 is 60. 35 to 59.8 HZ, unit 2 is 60.4 to 59.7 HZ, and unit 3 is 60.2 to 59.75 HZ, more continuous oscillation in unit 3, after the fault occurrence.

- **Stator voltage**

  Figure 4.23 show the stator voltage during the fault for Case 4, the voltage oscillation close for unit 1 from 1.1 to 0.96 pu, for unit 2 from 1.24 to 0.92 pu, and for unit 3 from 1.16 to 0.86 pu during the fault, and it start to recover after the operation of the circuit breakers to clean the fault. More continuous oscillation in unit3, after the fault occurrence.

- **Rotor angle**

  Figure 4.22 show the rotor angle during the fault for Case 4, the rotor angle oscillated close for unit 1 from 10° to -30°, for unit 2 from 88° to 58°, and for unit 3 from 61° to 50°.

- **Excitation**

  Figure 4.21 show the stator voltage during the fault for Case 4, the support voltage for unit 1 from 3.6 to 0 pu , for unit 2 from 4 to - 0.5 pu, and for unit 3 from 3.4 to 0 pu, more continuous oscillation in unit 3, after the fault occurrence.

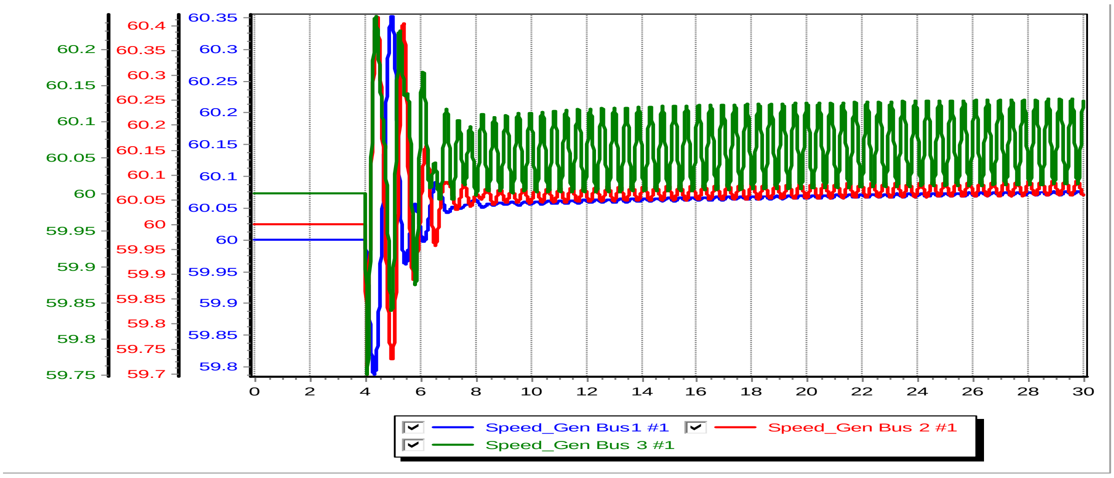

Figure 4.20: Case 4-AC1A with PSS1A

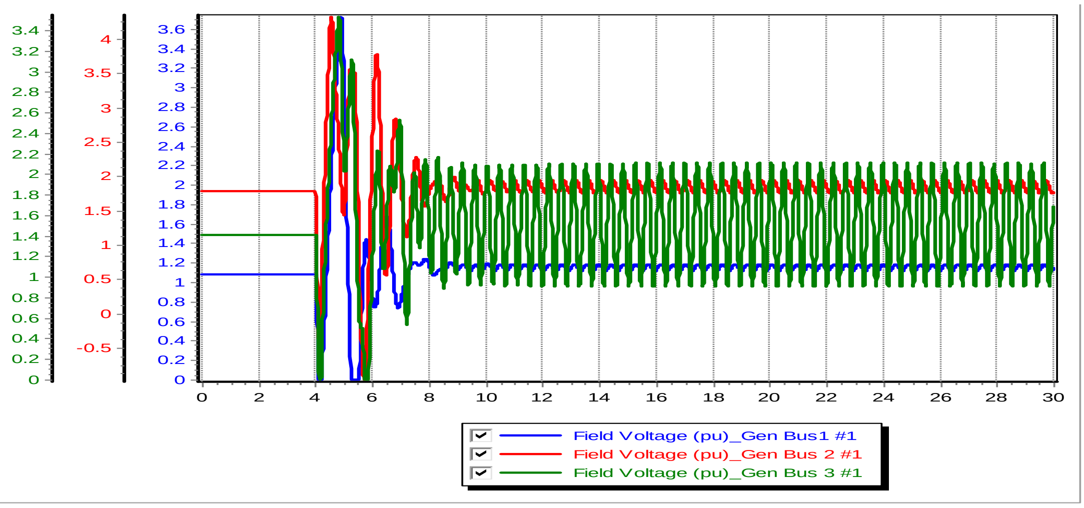

Figure 4.21: Case 4-AC1A with PSS1A

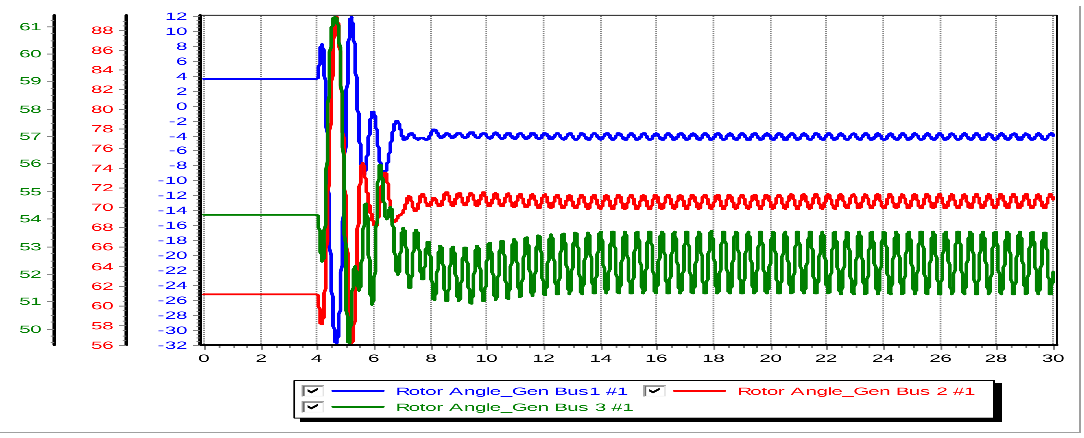

Figure 4.22: Case 4-AC1A with PSS1A

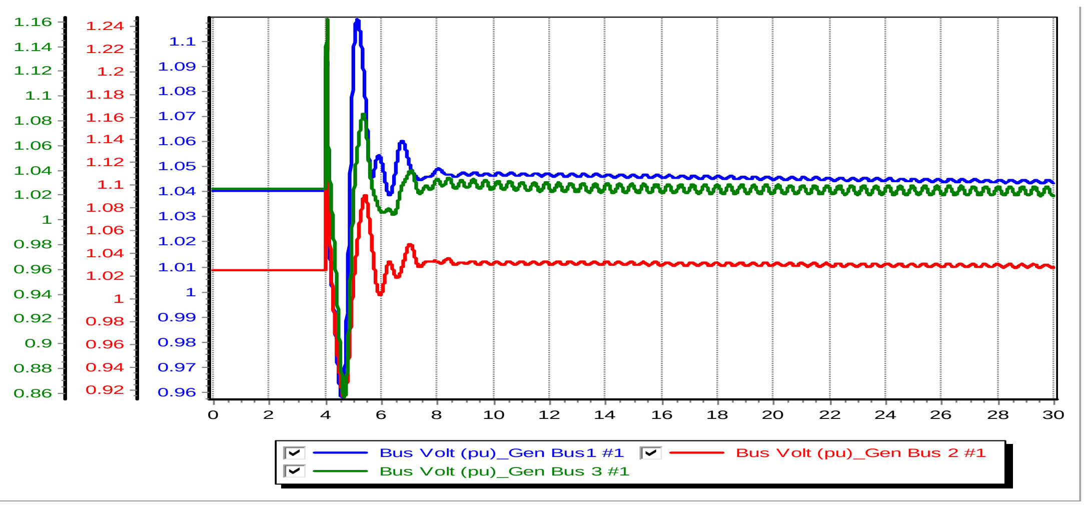

Figure 4.23: Case 4-AC1A with PSS1A

Case 5:

- **Rotor speed**

  Figure 4.24 show the rotor speed during the fault for Case 5. It can be seen in the plots that the highest oscillation are for unit 1 is 60. 3 to 59.8 HZ, unit 2 is 60.5 to 59.6 HZ and unit 3 is 60.25 to 59.75 HZ. It takes approximately 12 seconds after the fault occurrence to return to steady state.

- **Stator voltage**

  Figure 4.27 show the stator voltage during the fault for Case 5, the voltage oscillation close for unit 1 from 1.09 to 0.99 pu, for unit 2 from 1.24 to 0.9 pu, and for unit 3 from 1.16 to 0.88 pu during the fault, and it start to recover after the operation of the circuit breakers to clean the fault. Approximately 12 seconds after the fault occurrence to return to steady state.

- **Rotor angle**

  Figure 4.26 show the rotor angle during the fault for Case 5, the rotor angle oscillated close for unit 1 from 15° to -30°, for unit 2 from 90° to 52°, and for unit 3 from 59.5° to 49°.

- **Excitation**

  Figure 4.25 show the stator voltage during the fault for Case 5, the support voltage for unit 1 from 2.4 to 0.4 pu, for unit 2 from 4.5 to 0 pu, and for unit 3 from 3.8 to 0.2 pu, approximately 10 seconds to return to steady state.

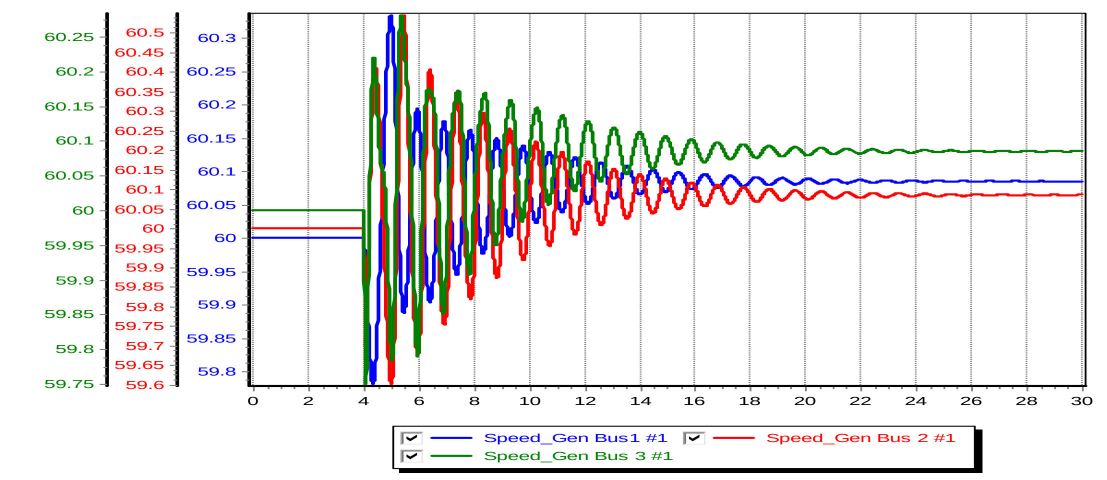

Figure 4.24: Case 5-AC1A without - PSS

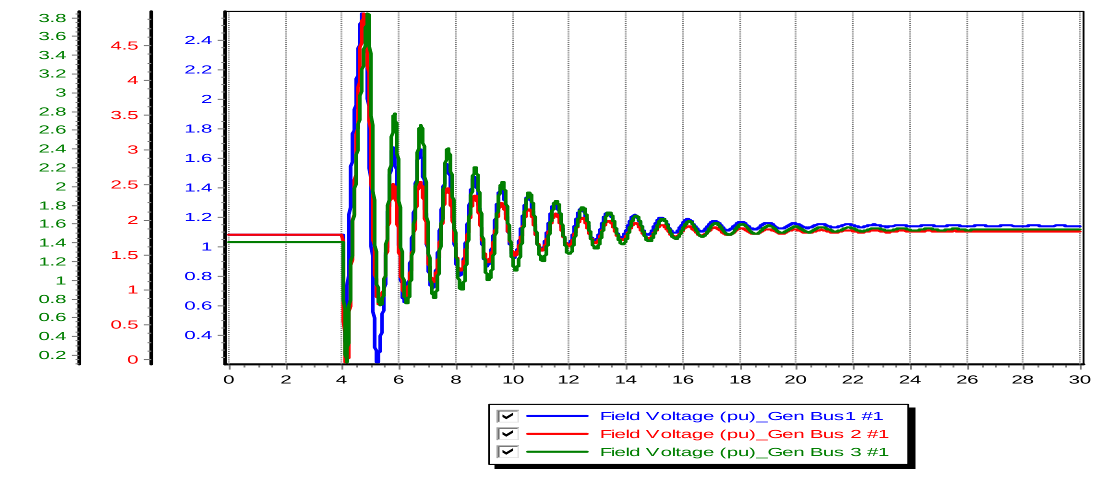

Figure 4.25: Case 5-AC1A without – PSS

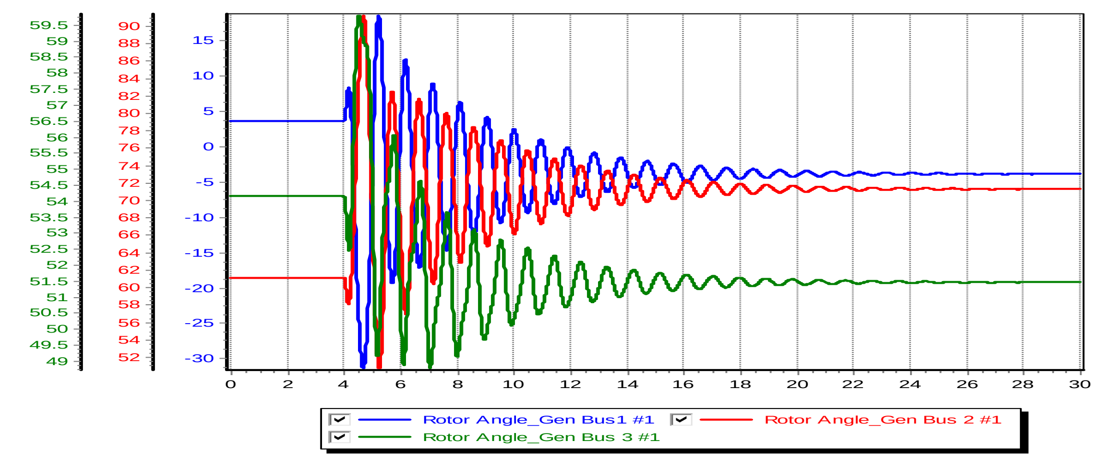

Figure 4.26: Case 5-AC1A without - PSS

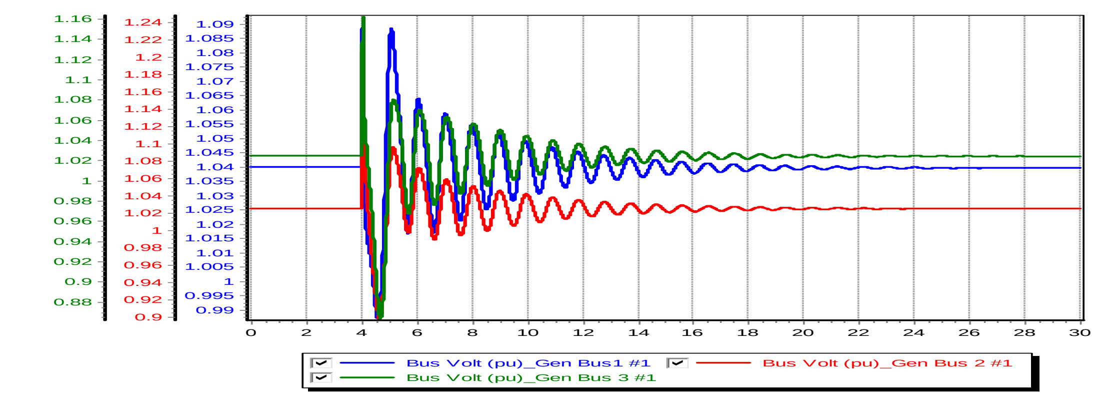

Figure 4.27: Case 5-AC1A without - PSS

Case 6:

- **Rotor speed**

  Figure 4.28 show the rotor speed during the fault for Case 6. It can be seen in the plots that the highest oscillation are for unit 1 is 60.3 to 59.8 HZ unit 2 is 60.35 to 59.7 HZ and unit 3 is 60.2 to 59.75 HZ. It takes approximately 4 seconds after the fault occurrence to return to steady state.

- **Stator voltage**

  Figure 4.31 show the stator voltage during the fault for Case 6, the voltage oscillation close for unit 1 from 1.09 to 0.96 pu, for unit 2 from 1.24 to 0.94 pu, and for unit 3 from 1.16 to 0.9 pu during the fault, and it start to recover after the operation of the circuit breakers to clean the fault. Approximately 4 seconds after the fault occurrence to return to steady state.

- **Rotor angle**

  Figure 4.30 show the rotor angle during the fault for Case 6, the rotor angle oscillated close for unit 1 from 10° to -26° for unit 2 from 86° to 58° and for unit 3 from 60.5° to 49°.

- **Excitation**

  Figure 4.29 show the stator voltage during the fault for Case 6, the support voltage for unit 1 from 3.2 to 0 pu for unit 2 from 3.4 to 0 pu, and for unit 3 from 3.6 to 0.2 pu, approximately 10 seconds to return to steady state.

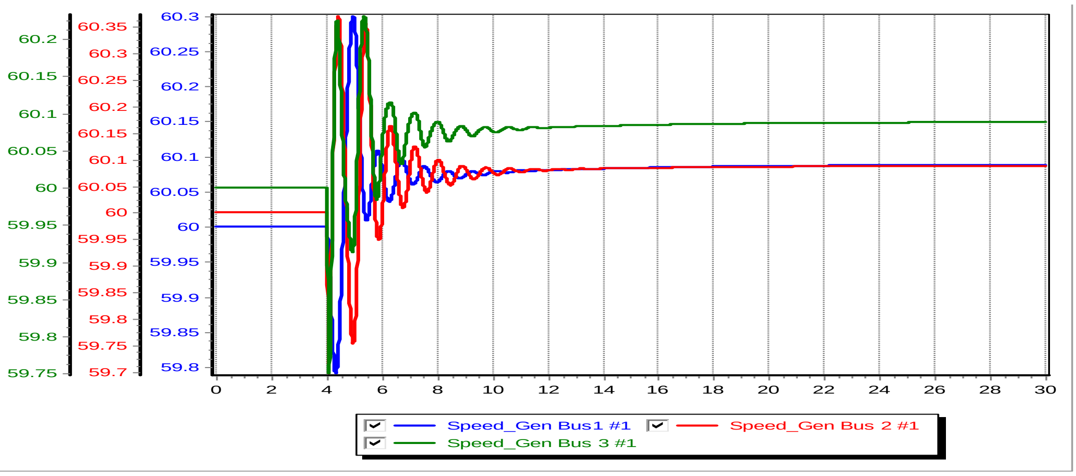

Figure 4.28: Case 6-AC1A with - PSS2A

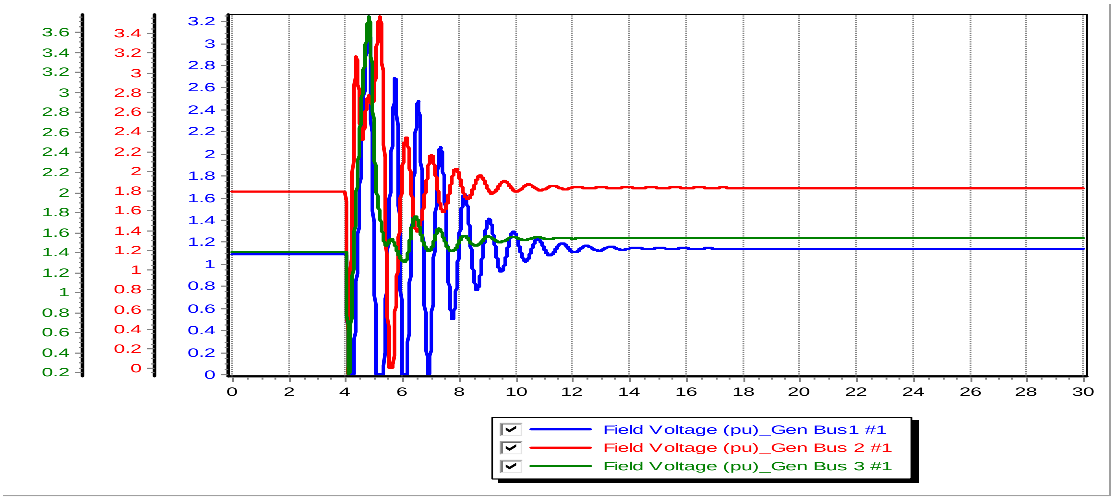

Figure 4.29: Case 6-AC1A with - PSS2A

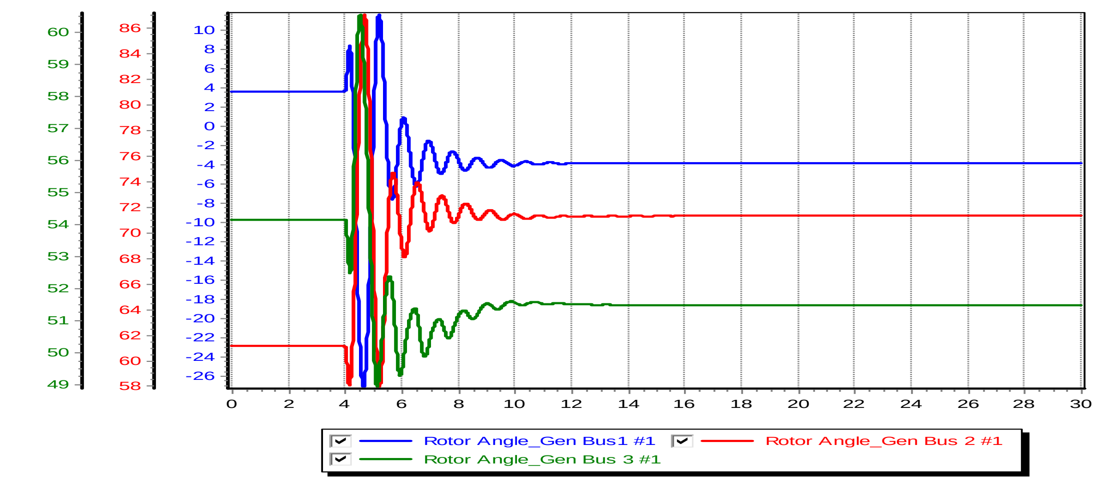

Figure 4.30: Case 6-AC1A with - PSS2A

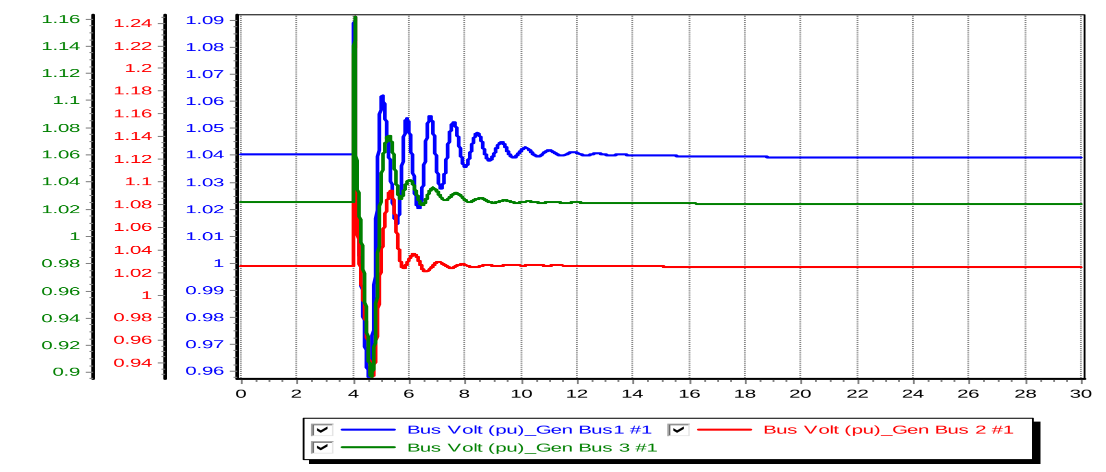

Figure 4.31: Case 6-AC1A with - PSS2A

- **The Acceleration :**

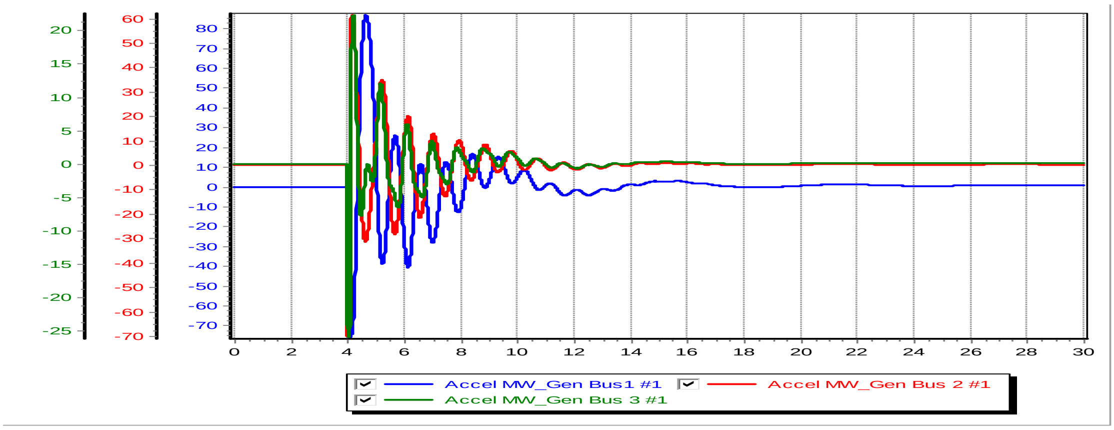

Figure 4.32: Acceleration- ST1A without PSS

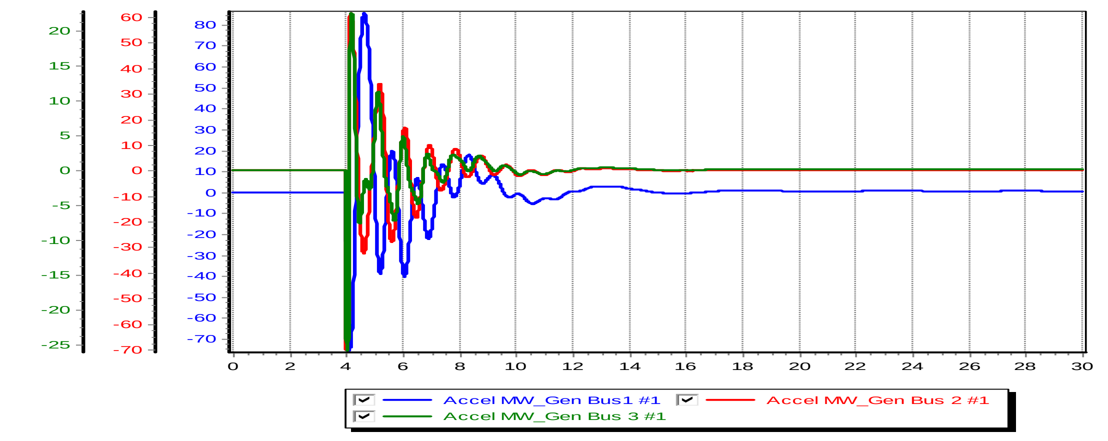

Figure 4.33: Acceleration- ST1A with PSSA1

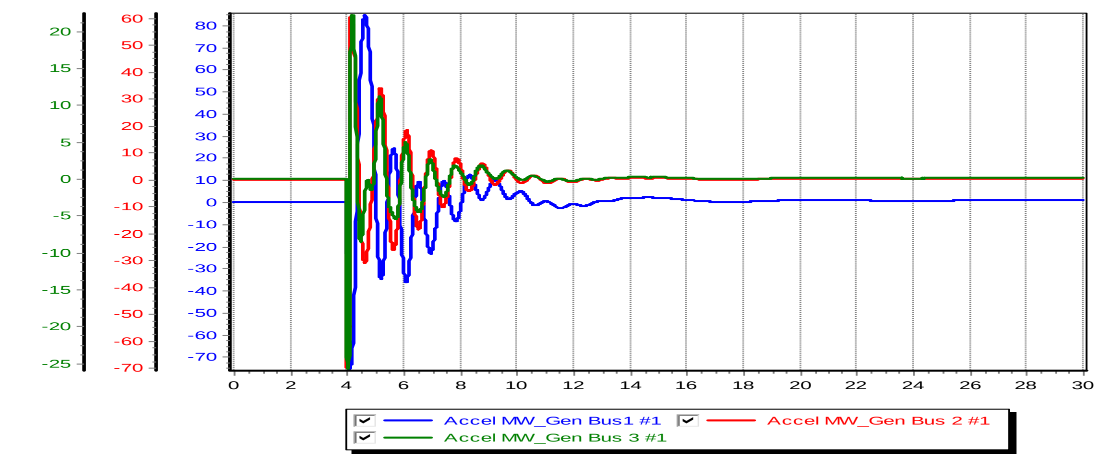

Figure 4.34: Acceleration- ST1A with PSS2A

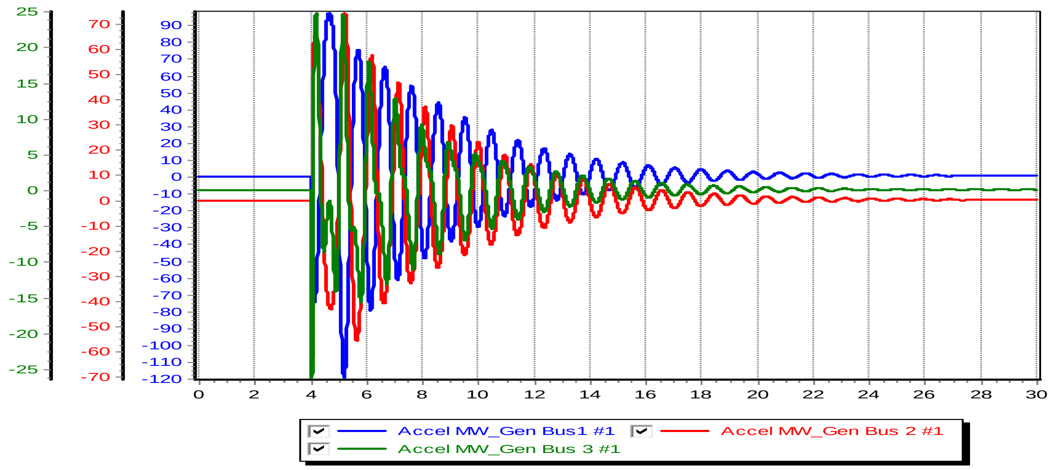

Figure 4.35: Acceleration- AC1A without PSS

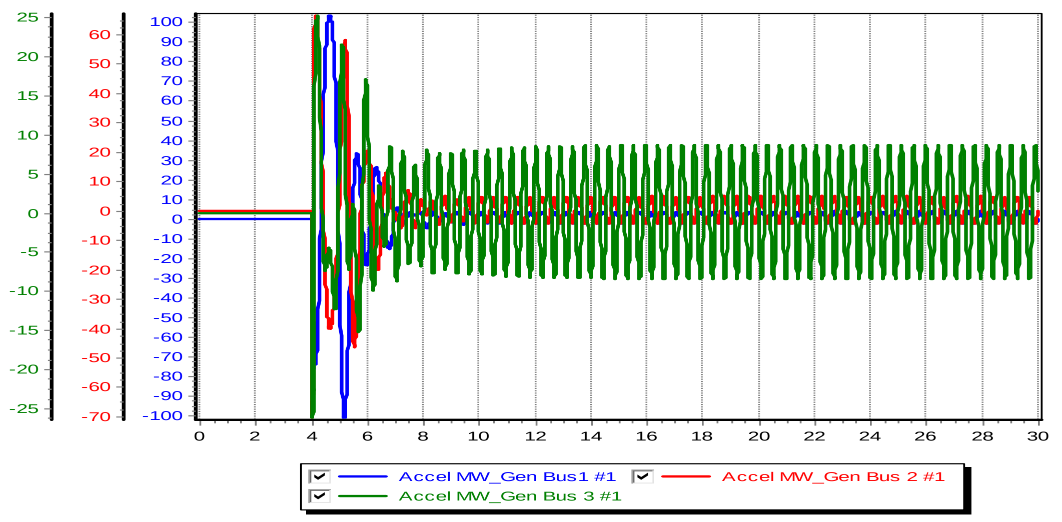

Figure 4.36: Acceleration - AC1A with PSS1A

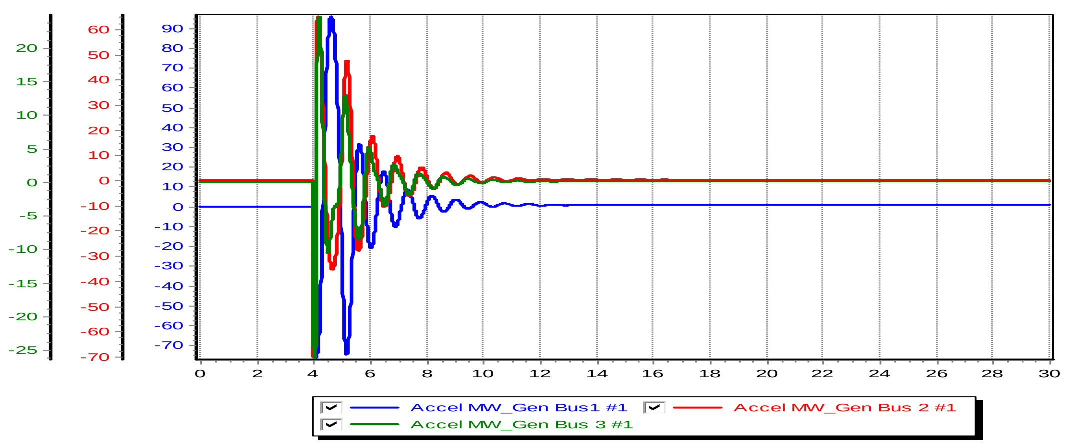

Figure 4.37: Acceleration- AC1A with PSS2A

- **Special case the fault cleared t = 0.3 second**

The ST1A without - PSS is stable with time fault cleared at time, t = 0.3 second. The system was able to be stable. But AC1A without-PSS show that with time 0.3s is unstable. It was clear and were shown from Figure 4.38 to Figure 4.42.

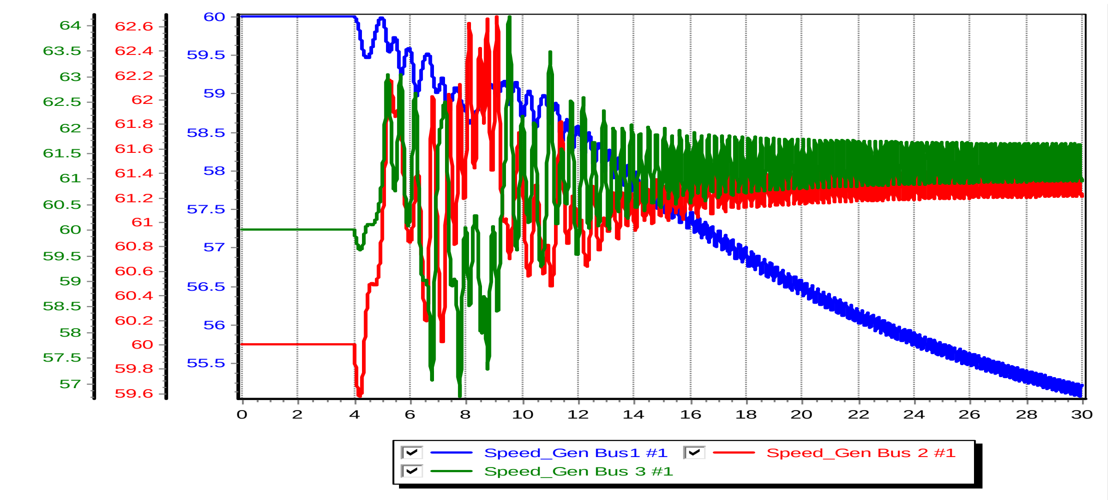

Figure 4.38: AC1A without - PSS is unstable with time 0.3s

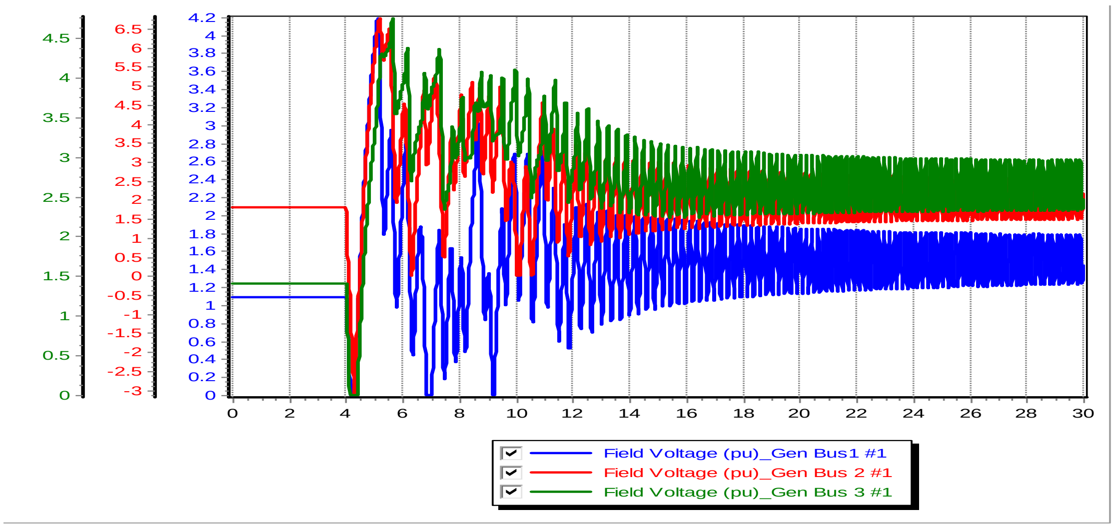

Figure 4.39: AC1A without - PSS is unstable with time 0.3s

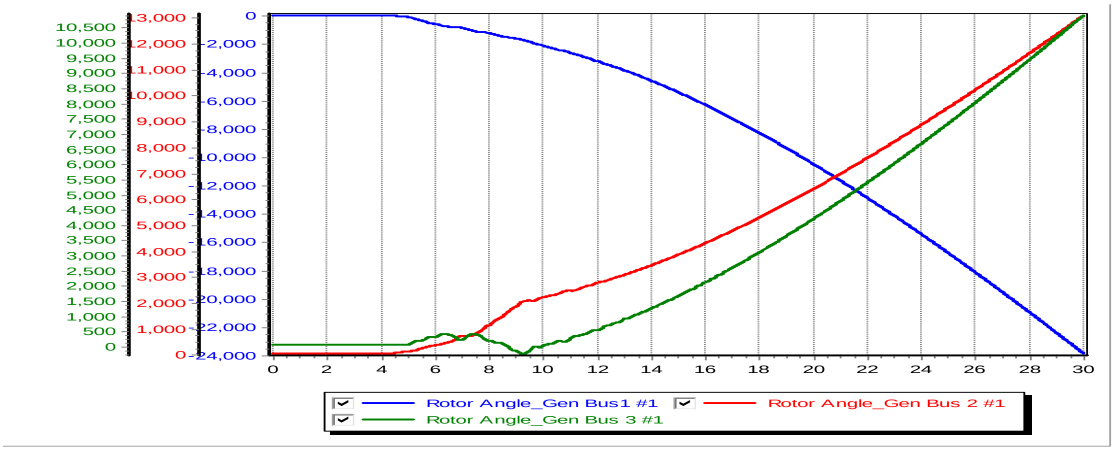

Figure 4.40: AC1A without - PSS is unstable with time 0.3s

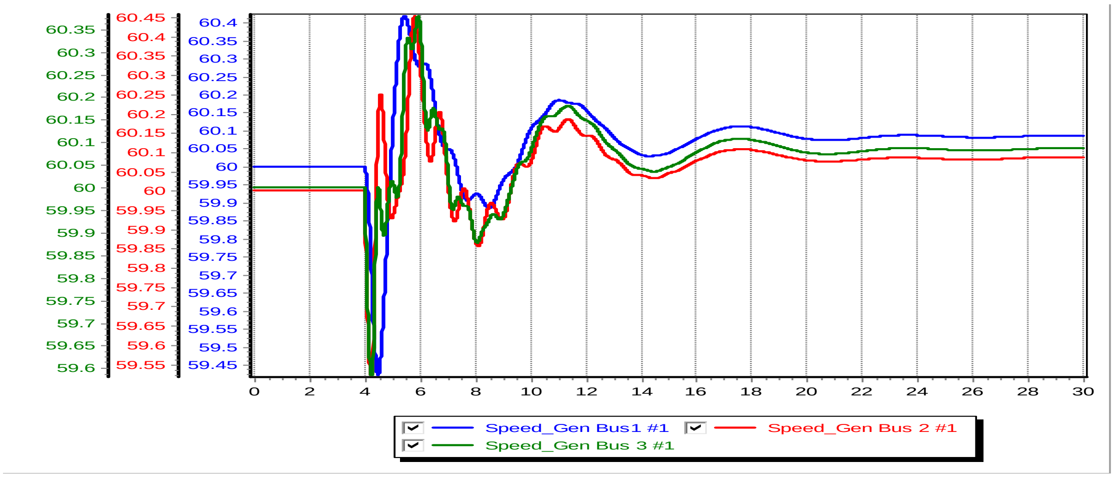

Figure 4.41: ST1A without - PSS is stable with time 0.3s

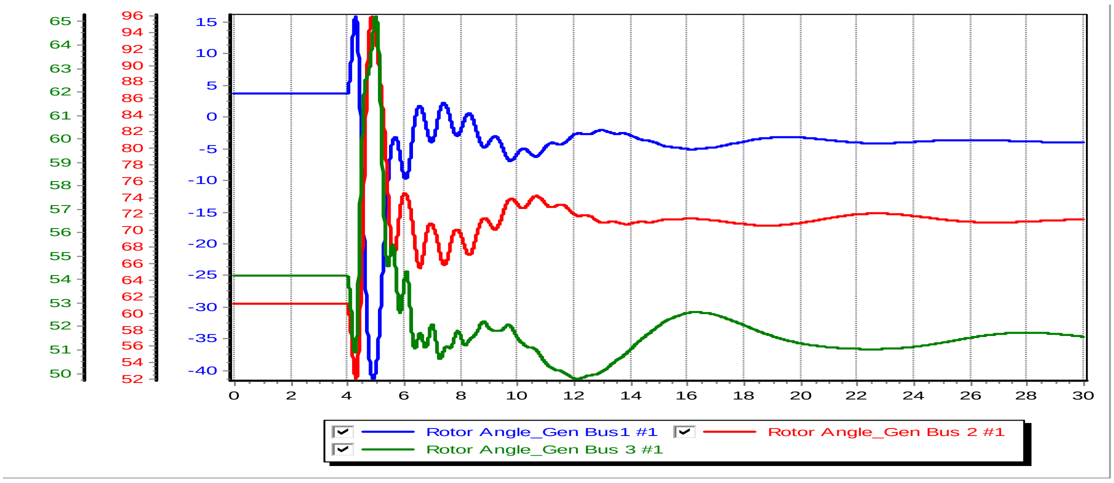

Figure 4.42: ST1A without - PSS is stable with time 0.3s

CHAPTER 5

CONCLUSION

5.1 Conclusion

This work has discussed, the effects of different types of excitation systems, power system stabilizer (PSS) and automatic voltage regulator (AVR), to ameliorate the transient stability of generator in power system (phase to ground fault). The design problem for AVR and PSS is studied to find the performance difference between the models. The studied system consists of a multi-machine with slack bus system. The types of excitation systems, AVR IEEE AC1A, ST1A excitation systems, type PSS1A power system stabilizer and type PSS2A power system stabilizer were chosen. As a result of the study and with reference to Chapter 4, simulations and results the ST1A model provides greater stability to the power system was discussed in (Eshraghnia and Kleen, 2014), and the ST1A model under study more responsive compared to ACA1. The results correspond with (Zhang and Xu, 2007). The excitation system type AC1A with medium response, while the excitation system type ST1A with high response. And the results was reported in (Slenduhhov and Kilter, 2013). From the results obtained, and it was clear that in Case 1 there is harmony between type ST1A and Type PSS1A power system stabilizer. In Case 2, and with rotor speed the type ST1A excitation system model without stabilizer It takes about 9 seconds to response to normal value. Also in Case 3, ST1A has the same performance with PSS2A stabilizer. There is a little different between Case 1, 2 and 3. But The PSS1A, PSS2A affect positively in ST1A.

In Case 4, type AC1A excitation system model, there is voltage oscillation output, also PSS1A is not good choice for type AC1A, this is not best case for AC1A and with more oscillation in unit 3, but with fast response approximately 4 seconds after the fault occurrence to return to steady state. The cause of oscillation in unit 3 is the steam turbine inertia constant (H) at unit 3 and damping coefficient compared to other units.

In Case 5 type AC1A excitation system model without stabilizer the results better than Case 4. It is medium response, was reported in (Bhaskar et al., 2000).

In Case 6 the system is the best case, and it passed the test time with constant vibration and show that PSS2A, is suitable with AC1A in this case and have a better damping.

Both PSS1A-PSS and PSS2A-PSS are first analyzed. The fault analysis is carried out for the Chapter 4 test system with both PSS1A-PSS and PSS2A-PSS. And for the rotor angle during the fault. It is observed that ST1A without PSS and AC1A with PSS2A resulted in better transient response for single phase faults. This is consistent with previous research, because the ST1A has fast response, was discussed in (Lubosuy, 2006). For all cases, the PSS1A affect positively with ST1A, but negatively with AC1A resulted in bad dynamic response with low frequency oscillations after clearing the fault. But we cannot say that the PSS1A is not suitable to AC1A, because there are other factors affecting, Xd, Xq, $Td0^{'}$, inertia constant (H) and damping coefficient (D).

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APPENDIX A

Reduced And Generator Data

Table A.1: Generator data

Generator no.	1	2	3
Rated MVA	247.5	192.0	128.0
kV	16.5	18.0	13.8
H (s)	23.64	6.4	3.01
Power factor	1.0	0.85	0.85
Type	Hydro	Steam	Steam
Speed	180 r/min	3600 r/min	3600 r/min
x_d	0.1460	0.8958	1.3125
x'_d	0.0608	0.1198	0.1813
x_q	0.0969	0.8645	1.2578
x'_q	0.0969	0.1969	0.25
x_l (leakage)	0.0336	0.0521	0.0742
T_{do}	8.96	6.00	5.89
T'_{qo}	0	0.535	0.600
Stored energy at rated speed	2364 MW s	640 MW s	301 MW s

Note: Reactance values are in pu on a 100 MVA base. All time constants are in seconds.

Table A.2: Reduced Y matrices

Pre-fault network:

$$Y_{Rpf} = \begin{bmatrix} 0.8455-2.9883i & 0.2871+1.5129i & 0.2096+1.2256i \\ 0.2871+1.5129i & 0.4200-2.7239i & 0.2133+1.0879i \\ 0.2096+1.2256i & 0.2133+1.0879i & 0.2770-2.3681i \end{bmatrix}$$

During fault:

$$Y_{Rdf} = \begin{bmatrix} 0.6568-3.8160i & 0 & 0.0701+0.6306i \\ 0 & 0-5.4855i & 0 \\ 0.0701+0.6306i & 0 & 0.1740-2.7959i \end{bmatrix}$$

After fault network:

$$Y_{Raf} = \begin{bmatrix} 1.1386-2.2966i & 0.1290+0.7063i & 0.1824+1.0637i \\ 0.1290+0.7063i & 0.3745-2.0151i & 0.1921+1.2067i \\ 0.1824+1.0637i & 0.1921+1.2067i & 0.2691-2.3516i \end{bmatrix}$$

APPENDIX B

Excitation System, AVR And PSS Models

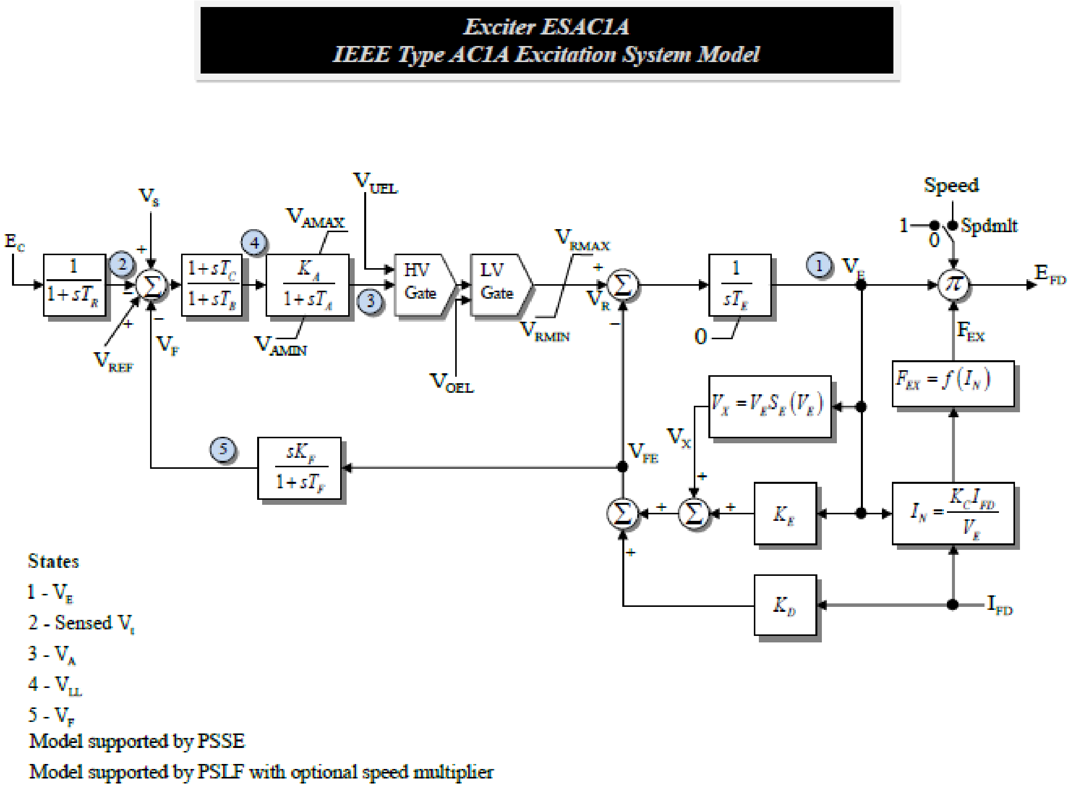

Figure B.1: AC1A Excitation system model

Table B.1: AC1A Data

$T_R = 0$	$K_F = 0.03$	$V_{AMIN} = -14.5$
$R_C = 0$	$T_F = 1.0$	$V_{RMAX} = 6.03$
$X_C = 0$	$K_E = 1.0$	$V_{RMIN} = -5.43$
$K_A = 400$	$T_E = 0.80$	$S_E[V_{E1}] = 0.10$
$T_A = 0.02$	$K_D = 0.38$	$V_{E1} = 4.18$
$T_B = 0$	$K_c = 0.20$	$S_E[V_{E2}] = 0.03$
$T_C = 0$	$V_{AMAX} = 14.5$	$V_{E2} = 3.14$

Exciter ESST1A and ESST1A_GE

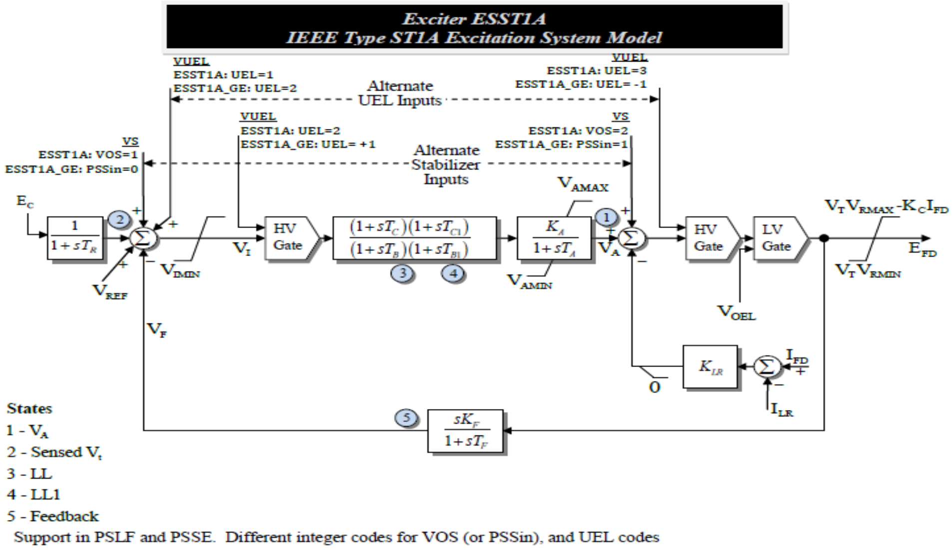

Figure B.2: ST1A Excitation system model

Table B.2 ST1A data

$K_A = 210.0$	$T_{B1} = 0$	$K_F = 0$
$T_A = 0$	$V_{RMAX} = 6.43$	$T_F = 0$ (not used)
$T_C = 1.0$	$V_{RMIN} = -6.0$	$K_{LR} = 4.54$
$T_B = 1.0$	$K_C = 0.038$	$I_{LR} = 4.4$
$T_{C1} = 0$	V_{IMAX}, V_{IMIN} (not represented)	

Stabilizer PSS1A

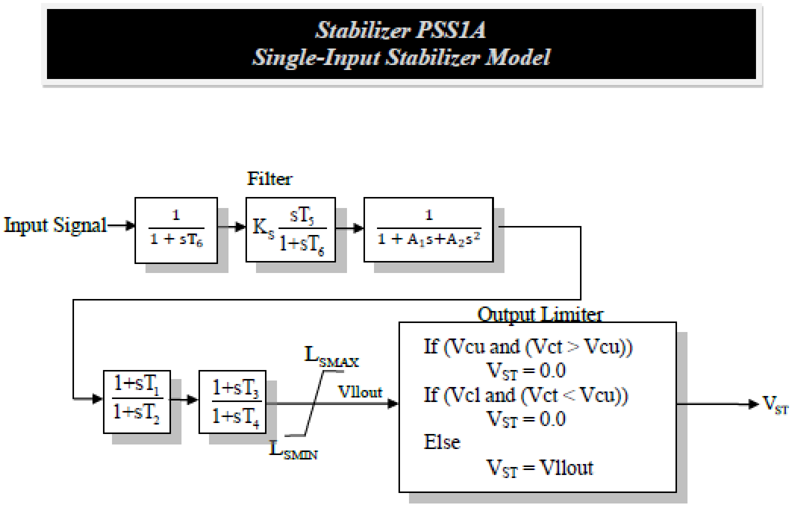

Figure B.3: PSS1A model

Table B.3: PSS1A data

Stabilizer	Type PSS1A with speed input	
	K_S	3.15
	T_1	0.76
	T_2	0.1
	T_3	0.76
	T_4	0.1
	$T_5 1$	0.0
	V_{STMAX}	0.09
	V_{STMIN}	−0.09

Table B.4: PSS1A data

Stabilizer	Type PSS1A with terminal frequency or speed (to represent internally compensated frequency) input	
	K_S	1.4 pu
	T_1	0.5
	T_2	0.06
	T_3	0.5
	T_4	0.06
	T_5	30.0
	T_6	0.016
	V_{STMAX}	0.05
	V_{STMIN}	−0.05

Stabilizer PSS2A

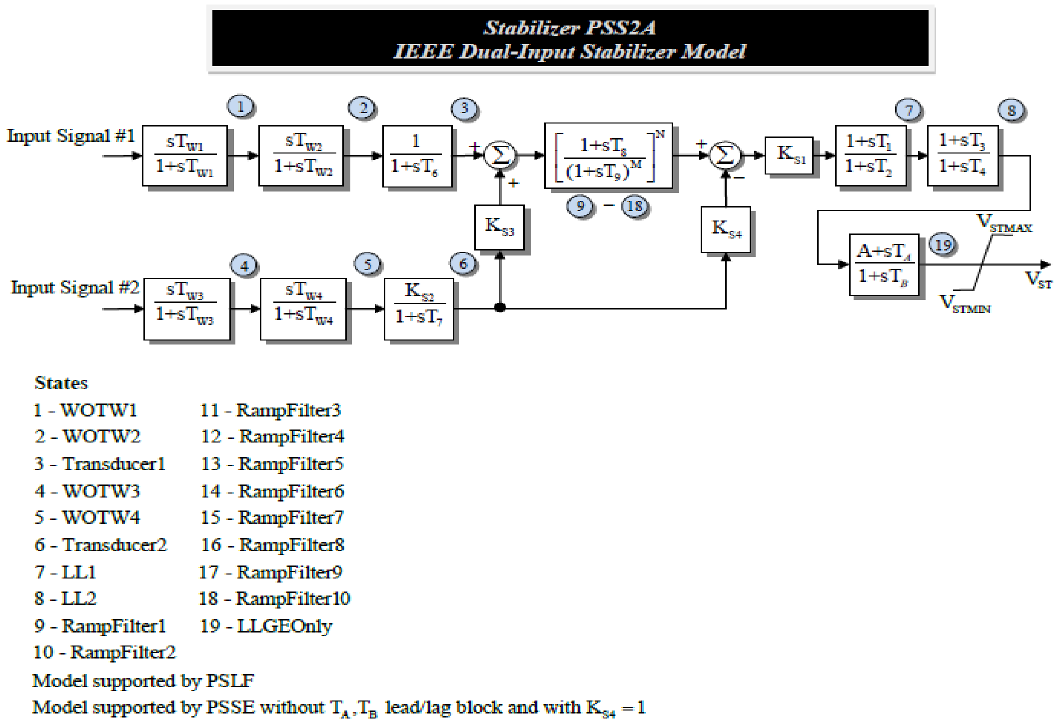

Figure B.4: PSS2A model

Table B.5: PSS2A data

V_{SI1} = speed input in pu	$T_{w4} = 0$
V_{SI2} = electrical power input in pu	$M = 2$
$K_{S1} = 20$	$N = 4$
$K_{S2} = 1.13 = T_7/2H$	$V_{STMAX} = 0.20$
$K_{S3} = 1$	$V_{STMIN} = -0.066$
$T_1 = T_3 = 0.16$	$T_6 = 0$
$T_2 = T_4 = 0.02$	$T_7 = 10$
H = synchronous machine inertia constant	$T_8 = 0.3$
$T_{W1} = T_{W2} = T_{W3} = 10$	$T_9 = 0.15$

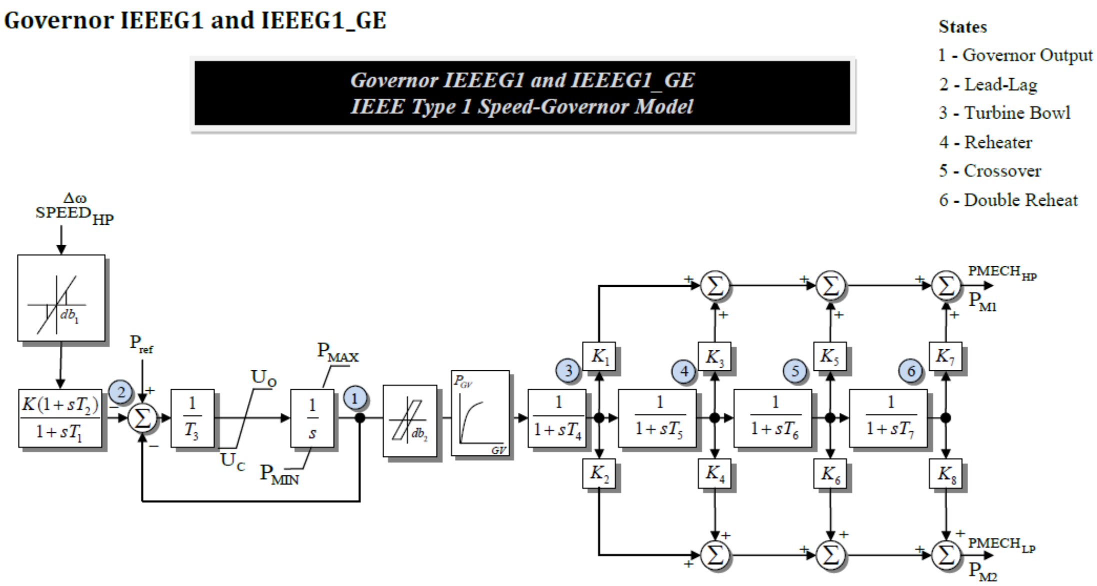

Figure B.5: IEEEG1 Governor

APPENDIX C

Before Fault And Fault Analysis

Table C.1: Before fault-generators

Name of Bus	Max Mvar	Min Mvar	Max MW	Min MW	AVR	AGC	Set Volt	Gen Mvar	Gen MW	Status
Bus1	9900	-9900	1000	0	YES	YES	1.04	27.04	71.64	Closed
Bus 2	9900	-9900	1000	0	YES	YES	1.025	6.65	163	Closed
Bus 3	9900	-9900	1000	0	YES	YES	1.025	-10.86	85	Closed

Table C.2: Before fault-bus data

Gen Mvar	Gen MW	Load Mvar	Load MW	Angle (Deg)	Volt (kV)	PU Volt	Nom kV	Name
27.04	71.64			0	17.16	1.04	16.5	Bus1
6.65	163			9.28	18.45	1.025	18	Bus 2
-10.86	85			4.67	14.145	1.025	13.8	Bus 3
				-2.22	235.932	1.02579	230	Bus 4
		50	125	-3.99	228.997	0.99564	230	Bus 5
		30	90	-3.69	232.912	1.01266	230	Bus 6
				3.72	235.928	1.02577	230	Bus 7
		35	100	0.73	233.654	1.01589	230	Bus 8
				1.97	237.442	1.03236	230	Bus 9

Table C.3: Before fault-lines and transformers

To Name	From Name	Mvar Loss	MW Loss	MVA From	Mvar From	MW From	Device Type
Bus1	Bus 4	3.12	0	75.5	-23.9	-71.6	Transformer
Bus 7	Bus 2	15.83	0	163.1	6.6	163	Transformer
Bus 3	Bus 9	4.1	0	86.3	15	-85	Transformer
Bus 4	Bus 5	-15.79	0.26	56.1	-38.7	-40.7	Line
Bus 4	Bus 6	-15.51	0.17	34.7	-16.5	-30.5	Line
Bus 5	Bus 7	-19.69	2.3	87	-8.4	86.6	Line
Bus 6	Bus 9	-31.53	1.35	63.4	-18.1	60.8	Line
Bus 8	Bus 7	-11.5	0.48	76.4	-0.8	76.4	Line
Bus 9	Bus 8	-21.18	0.09	34.2	-24.3	-24.1	Line

Table C.4: Before fault-loads

Name of Bus	Number of Bus	Mvar	MVA	Mvar	MW	Status
Bus 5	5	50	134.63	50	125	Closed
Bus 6	6	30	94.87	30	90	Closed
Bus 8	8	35	105.95	35	100	Closed

Table C.5: Fault analysis

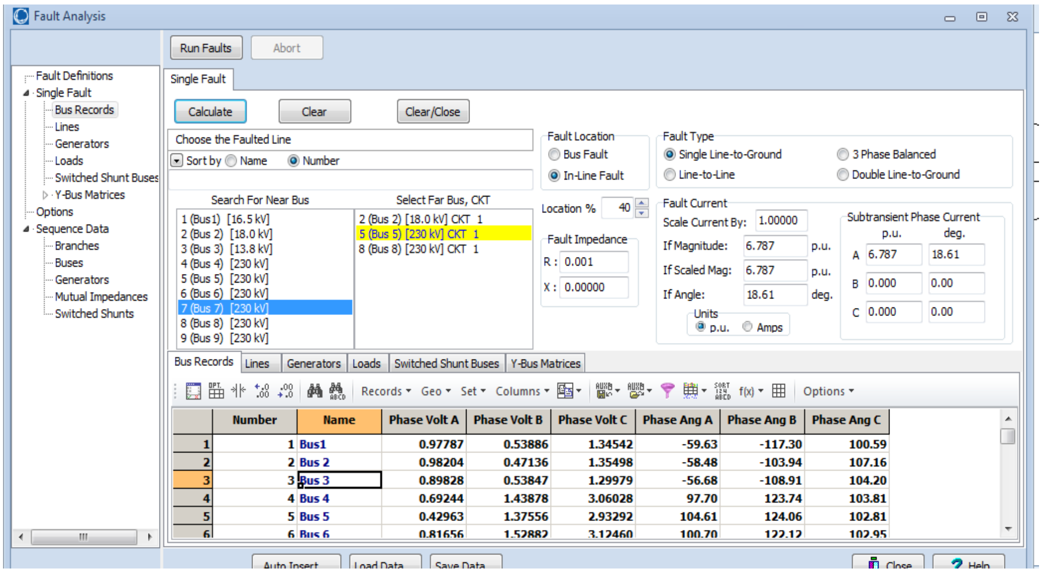

Table C.6: Fault-generators

Phase Ang C	Phase Ang B	Phase Ang A	Phase Cur C	Phase Cur B	Phase Cur A	Name of Bus	Bus
118.43	-168.94	-27.73	1.1365	1.01021	1.73142	Bus1	1
133.78	-132.78	-6.75	2.10693	1.65581	2.60041	Bus 2	2
137.77	-141.86	-12.13	1.31805	0.85957	1.68972	Bus 3	3

Table C.7: Fault-bus

Phase Ang C	Phase Ang B	Phase Ang A	Phase Volt C	Phase Volt B	Phase Volt A	Name
100.59	-117.3	-59.63	1.34542	0.53886	0.97787	Bus1
107.16	-103.94	-58.48	1.35498	0.47136	0.98204	Bus 2
104.2	-108.91	-56.68	1.29979	0.53847	0.89828	Bus 3
103.81	123.74	97.7	3.06028	1.43878	0.69244	Bus 4
102.81	124.06	104.61	2.93292	1.37556	0.42963	Bus 5
102.95	122.12	100.7	3.1246	1.52882	0.81656	Bus 6
106.08	124.15	90.71	2.90212	1.22711	0.40424	Bus 7
104.69	122.85	98.07	3.0028	1.36309	0.61741	Bus 8
105.29	121.91	95.61	3.11971	1.43991	0.84868	Bus 9
105.06	127.15	18.61	2.79	1.16903	0.00679	FaultPt

Table C.8: Fault-line

Phase Cur C To	Phase Cur B To	Phase Cur A To	Phase Cur C From	Phase Cur B From	Phase Cur A From	To Name	From Name
1.1365	1.01021	1.73142	1.1365	1.01021	1.73142	Bus1	Bus 4
2.10693	1.65581	2.60041	2.10693	1.65581	2.60041	Bus 7	Bus 2
1.31805	0.85957	1.68972	1.31805	0.85957	1.68972	Bus 3	Bus 9
0.68321	0.47841	2.11075	0.91813	0.30774	2.20629	Bus 4	Bus 5
0.5729	0.54996	0.86622	0.43234	0.32405	0.77769	Bus 4	Bus 6
0	0	0	0	0	0	Bus 5	Bus 7
1.02252	0.48437	2.62969	0.99578	0.6781	2.64344	Bus 5	FaultPt
0.82133	0.22426	0.6135	0.96478	0.69808	0.4118	Bus 6	Bus 9
0.8732	0.60317	1.7913	0.97741	0.79087	1.85687	Bus 8	Bus 7
0.99569	0.67801	4.25658	1.13037	0.86598	4.17474	FaultPt	Bus 7
0.41027	0.19457	1.40497	0.71609	0.14067	1.55689	Bus 9	Bus 8

Table C.9: Fault-loads

Phase Cur C	Phase Cur B	Phase Cur A	Name of Bus
1.89492	0.57346	1.53425	Bus 5
1.23868	0.45546	0.92229	Bus 6
1.40722	0.47159	1.06882	Bus 8

APPENDIX D

Transient Analysis

Table D.1: AC1A with PSS1A

Time Max Speed	Max Speed	Time Min Speed	Min Speed	Time Max Angle	Max Angle	Time Min Angle	Min Angle	Original Angle	Name of Bus
4.975	60.351	4.341	59.787	5.208	11.869	4.675	-31.774	3.586	Bus1
4.433	60.418	4.108	59.72	4.683	89.349	5.233	56.173	61.1	Bus 2
4.391	60.246	4.108	59.76	4.625	61.326	5.125	49.478	54.138	Bus 3

Table D.2: AC1A with PSS1A

Name of Bus	Original Efd	Max-Min PMech	Time Max PMech	Max PMech	Time Min PMech	Min PMech	Original PMech
Bus1	1.0821	18.939	4.508	78.576	5.141	59.637	71.645
Bus 2	1.7893	13.208	0	163	4.616	149.792	163
Bus 3	1.403	10.789	4.233	89.062	4.608	78.273	85

Table D.3: AC1A with PSS1A

Name of Bus	Max-Min Vs	Max Vs	Min Vs	Max Ifd	Min Ifd	Original Ifd	Max Efd	Min Efd
Bus1	0.2	0.1	-0.1	1.2161	1.0821	1.0821	3.7211	0
Bus 2	0.2	0.1	-0.1	2.4521	1.367	1.7893	4.3209	-0.9624
Bus 3	0.2	0.1	-0.1	1.8824	1.2125	1.403	3.5302	0

Table D.4: AC1A with PSS1A

Time Max Hz	Max Hz	Time Min Hz	Min Hz	Time Max Volt	Max Volt	Time Min Volt	Min Volt	Original Volt	Name
5	60.2888	4.35	59.8455	5.15	1.1086	4.6	0.9578	1.04	Bus1
4.5	60.3886	4.108	59.7586	4.108	1.0968	4.666	0.9135	1.025	Bus 2
4.5	60.225	4.108	59.7972	5.366	1.0857	4.683	0.8563	1.025	Bus 3
4.966	60.2404	4.108	59.8794	5.183	1.0742	4.65	0.8743	1.0258	Bus 4
4.966	60.2404	4.108	59.851	5.183	1.0201	4.65	0.8303	0.9956	Bus 5
5.216	60.1523	4.108	59.8527	5.233	1.057	4.666	0.7986	1.0127	Bus 6
4.5	60.3466	4.108	59.7836	4.108	1.0867	4.683	0.8761	1.0258	Bus 7
4.516	60.2932	4.108	59.7919	5.366	1.0695	4.683	0.8356	1.0159	Bus 8
4.516	60.2134	4.108	59.8048	5.35	1.0865	4.683	0.8351	1.0324	Bus 9

Table D.5: AC1A with PSS2A

Time Max Speed	Max Speed	Time Min Speed	Min Speed	Time Max Angle	Max Angle	Time Min Angle	Min Angle	Original Angle	Name of Bus
4.958	60.3	4.333	59.791	5.208	11.55	4.65	-27.156	3.586	Bus1
4.425	60.37	4.108	59.72	4.691	87.034	5.225	57.953	61.1	Bus 2
5.358	60.23	4.108	59.761	4.541	60.544	5.141	48.923	54.138	Bus 3

Table D.6: AC1A with PSS2A

Max-Min PMech	Time Max PMech	Max PMech	Time Min PMech	Min PMech	Original PMech	Max-Min Speed
17.11	4.5	78.411	5.141	61.301	71.645	0.5084
11.534	0	163	4.6	151.466	163	0.6498
11.719	4.233	89.049	5.558	77.33	85	0.4694

Table D.7: AC1A with PSS2A

Max Vs	Min Vs	Original Vs	Max Ifd	Min Ifd	Original Ifd	Max Efd	Min Efd	Original Efd
0.1	-0.1	0	1.172	1.076	1.0821	3.2403	0	1.0821
0.1	-0.0667	0	2.3245	1.386	1.7893	3.567	-0.0609	1.7893
0.075	-0.0216	0	1.8803	1.2529	1.403	3.7558	0.1794	1.403

Table D.8: AC1A with PSS2A

Time Max Hz	Max Hz	Time Min Hz	Min Hz	Time Max Volt	Max Volt	Time Min Volt	Min Volt	Original Volt	Name
4.983	60.2481	4.35	59.8495	5.058	1.062	4.583	0.9579	1.04	Bus1
4.466	60.3373	4.108	59.7588	4.108	1.0966	4.683	0.9275	1.025	Bus 2
5.408	60.2134	4.108	59.7973	5.291	1.0737	4.666	0.8965	1.025	Bus 3
4.975	60.2087	4.108	59.8794	5.1	1.0325	4.616	0.8871	1.0258	Bus 4
4.975	60.2087	4.108	59.8511	0	0.9956	4.616	0.8424	0.9956	Bus 5
5.275	60.1408	4.108	59.8528	5.175	1.0267	4.65	0.8298	1.0127	Bus 6
4.466	60.3004	4.108	59.7837	4.108	1.0864	4.683	0.8997	1.0258	Bus 7
4.466	60.2543	4.108	59.792	4.108	1.0648	4.666	0.8683	1.0159	Bus 8
5.408	60.21	4.108	59.8048	5.275	1.0741	4.666	0.8756	1.0324	Bus 9

Table D.9: AC1A without PSS

Time Max Speed	Max Speed	Time Min Speed	Min Speed	Time Max Angle	Max Angle	Time Min Angle	Min Angle	Original Angle	Name of Bus
4.991	60.334	4.35	59.781	5.233	18.442	4.683	-31.37	3.586	Bus1
5.45	60.544	5.008	59.602	4.691	91.172	5.25	50.71	61.1	Bus 2
5.366	60.28	4.108	59.76	4.533	59.781	7.05	48.774	54.138	Bus 3

Table D.10: AC1A without PSS

Max-Min PMech	Time Max PMech	Max PMech	Time Min PMech	Min PMech	Original PMech
18.438	4.516	78.85	5.158	60.412	71.645
16.752	0	163	5.616	146.248	163
13.6	5.166	90.145	5.608	76.545	85

Table D.11: AC1A without PSS

Max Vs	Min Vs	Original Vs	Max Ifd	Min Ifd	Original Ifd	Max Efd	Min Efd	Original Efd
0	0	0	1.2326	1.0821	1.0821	2.5811	0.2163	1.0821
0	0	0	2.4774	1.3588	1.7893	4.9545	-0.0455	1.7893
0	0	0	1.8702	1.2465	1.403	3.8404	0.1219	1.403

Table D.12: AC1A without PSS

Time Max Hz	Max Hz	Time Min Hz	Min Hz	Time Max Volt	Max Volt	Time Min Volt	Min Volt	Original Volt	Name
5	60.2686	4.366	59.839	5.083	1.0884	4.6	0.9868	1.04	Bus1
5.483	60.4084	5.041	59.6991	4.108	1.0969	4.65	0.8979	1.025	Bus 2
5.45	60.2338	4.108	59.7971	5.158	1.0803	4.683	0.8633	1.025	Bus 3
4.958	60.2239	4.266	59.8792	5.116	1.0603	4.65	0.9004	1.0258	Bus 4
4.958	60.2239	4.108	59.851	5.116	1.0069	4.65	0.855	0.9956	Bus 5
4.883	60.1478	4.108	59.8527	5.15	1.0532	4.683	0.8186	1.0127	Bus 6
5.483	60.3621	5.05	59.7453	5.15	1.091	4.666	0.8652	1.0258	Bus 7
5.483	60.3063	4.108	59.7918	5.15	1.0754	4.683	0.8308	1.0159	Bus 8
5.466	60.2284	4.108	59.8047	5.15	1.0864	4.683	0.8407	1.0324	Bus 9

Table D.13: ST1A with PSS1A

Time Max Speed	Max Speed	Time Min Speed	Min Speed	Time Max Angle	Max Angle	Time Min Angle	Min Angle	Original Angle	Name of Bus
5.008	60.257	4.35	59.785	4.167	8.356	4.666	-24.719	3.586	Bus1
5.408	60.345	4.108	59.715	4.683	85.127	4.167	57.869	61.1	Bus 2
5.341	60.235	4.108	59.763	4.533	59.003	6.041	49.942	54.138	Bus 3

Table D.14: ST1A with PSS1A

Name of Bus	Time Max PMech	Max PMech	Time Min PMech	Min PMech	Original PMech
Bus1	4.516	78.752	5.208	62.501	71.645
Bus 2	0	163	5.583	151.597	163
Bus 3	4.233	89.066	5.575	76.674	85

Table D.15: ST1A with PSS1A

Name of Bus	Max Vs	Min Vs	Original Vs	MaxI fd	Min Ifd	Original Ifd	Max Efd	Min Efd	Original Efd
Bus1	0.0853	-0.1	0	1.1692	1.0821	1.0821	1.6265	0.6565	1.0821
Bus 2	0.1	-0.1	0	2.2706	1.4267	1.7893	2.5481	1.2624	1.7893
Bus 3	0.1	-0.1	0	1.7722	1.2644	1.403	2.2939	0.8874	1.403

Table D.16: ST1A with PSS1A

Time Max Hz	Max Hz	Time Min Hz	Min Hz	Time Max Volt	Max Volt	Time Min Volt	Min Volt	Original Volt	Name
5.066	60.2204	4.366	59.8397	6.833	1.072	4.633	0.9777	1.04	Bus1
5.433	60.3066	4.108	59.7681	4.108	1.1026	4.733	0.9298	1.025	Bus 2
5.416	60.2397	4.108	59.803	6.916	1.0772	4.716	0.9019	1.025	Bus 3
5.108	60.1957	4.316	59.8811	6.116	1.0399	4.666	0.9076	1.0258	Bus 4
5.108	60.1957	4.108	59.8555	0	0.9956	4.666	0.8619	0.9956	Bus 5
5.333	60.1895	4.108	59.857	6.125	1.0295	4.683	0.8514	1.0127	Bus 6
5.433	60.2892	4.108	59.7916	4.108	1.0917	4.716	0.9057	1.0258	Bus 7
5.433	60.2683	4.108	59.7992	4.108	1.0692	4.7	0.8772	1.0159	Bus 8
5.416	60.2388	4.108	59.8107	6.916	1.0739	4.7	0.8867	1.0324	Bus 9

Table D.17: ST1A with PSS2A

Time Max Hz	Max Hz	Time Min Hz	Min Hz	Time Max Volt	Max Volt	Time Min Volt	Min Volt	Original Volt	Name
5.075	60.2255	4.366	59.8412	6.866	1.0515	4.633	0.9802	1.04	Bus1
5.466	60.3292	4.108	59.7682	4.108	1.1025	4.733	0.9255	1.025	Bus 2
5.45	60.2664	4.108	59.8032	6.983	1.0732	4.716	0.8986	1.025	Bus 3
5.125	60.2017	4.3	59.8818	0	1.0258	4.666	0.9094	1.0258	Bus 4
5.125	60.2017	4.108	59.8556	0	0.9956	4.666	0.8636	0.9956	Bus 5
5.4	60.2084	4.108	59.8571	6.95	1.017	4.683	0.8518	1.0127	Bus 6
5.466	60.3126	4.108	59.7917	4.108	1.0916	4.716	0.9016	1.0258	Bus 7
5.458	60.2925	4.108	59.7993	4.108	1.069	4.716	0.8735	1.0159	Bus 8
5.45	60.2642	4.108	59.8109	4.108	1.0701	4.7	0.884	1.0324	Bus 9

Table D.18: ST1A with PSS2A

Time Max Speed	Max Speed	Time Min Speed	Min Speed	Time Max Angle	Max Angle	Time Min Angle	Min Angle	Original Angle	Name of Bus
5.025	60.261	4.35	59.787	4.167	8.358	4.675	-24.876	3.586	Bus1
5.433	60.367	4.108	59.715	4.691	85.218	4.167	57.866	61.1	Bus 2
5.383	60.267	4.108	59.763	4.533	59.446	6.941	49.899	54.138	Bus 3

Table D.19: ST1A with PSS2A

Name of Bus	Max-Min PMech	Time Max PMech	Max PMech	Time Min PMech	Min PMech	Original PMech
Bus1	16.438	4.516	78.698	5.225	62.26	71.645
Bus 2	12.439	0	163	5.608	150.561	163
Bus 3	13.526	4.233	89.073	5.591	75.547	85

Table D.20: ST1A with PSS2A

Max Vs	Min Vs	Original Vs	MaxIfd	MinIfd	Original Ifd	Max Efd	Min Efd	Original Efd
0.1	-0.1	0	1.1632	1.0821	1.0821	1.6444	0.6271	1.0821
0.1	-0.0638	0	2.2654	1.4324	1.7893	2.4768	1.2897	1.7893
0.0741	-0.0127	0	1.7683	1.2724	1.403	2.1219	0.9252	1.403

Table D.21: ST1A without PSS

Time Max Hz	Max Hz	Time Min Hz	Min Hz	Time Max Volt	Max Volt	Time Min Volt	Min Volt	Original Volt	Name
5.091	60.244	4.383	59.8349	6.983	1.0645	4.666	0.9813	1.04	Bus1
5.483	60.3467	4.108	59.7678	4.108	1.1028	4.733	0.9093	1.025	Bus 2
5.466	60.2747	4.108	59.8028	7.066	1.0721	4.733	0.8832	1.025	Bus 3
5.133	60.2186	4.333	59.8765	7.016	1.0341	4.683	0.9056	1.0258	Bus 4
5.133	60.2186	4.108	59.8554	0	0.9956	4.683	0.86	0.9956	Bus 5
5.391	60.2152	4.108	59.8569	7.016	1.0248	4.7	0.8412	1.0127	Bus 6
5.483	60.3278	4.108	59.7914	4.108	1.092	4.733	0.8843	1.0258	Bus 7
5.483	60.3049	4.108	59.799	4.108	1.0695	4.716	0.856	1.0159	Bus 8
5.466	60.2728	4.108	59.8106	4.108	1.0708	4.716	0.8675	1.0324	Bus 9

Table D.22: ST1A without PSS

Time Max Speed	Max Speed	Time Min Speed	Min Speed	Time Max Angle	Max Angle	Time Min Angle	Min Angle	Original Angle	Name of Bus
5.041	60.281	4.35	59.78	4.167	8.36	4.683	-26.583	3.586	Bus1
5.45	60.391	4.108	59.715	4.691	86.823	4.167	57.873	61.1	Bus 2
5.383	60.279	4.108	59.762	4.533	59.294	11.608	50.206	54.138	Bus 3

Table D.23: ST1A without PSS

Time Max PMech	Max PMech	Time Min PMech	Min PMech	Original PMech
4.525	78.942	5.241	61.506	71.645
0	163	5.633	149.729	163
4.233	89.088	5.608	75.042	85

Table D.24: ST1A without PSS

Max Vs	Min Vs	Original Vs	Max Ifd	Min Ifd	Original Ifd	Max Efd	Min Efd	Original Efd
0	0	0	1.1746	1.0821	1.0821	1.4333	0.9276	1.0821
0	0	0	2.287	1.4257	1.7893	2.2892	1.3284	1.7893
0	0	0	1.7766	1.2667	1.403	2.0499	1.001	1.403

APPENDIX E

Differential-Algebraic Equations Method

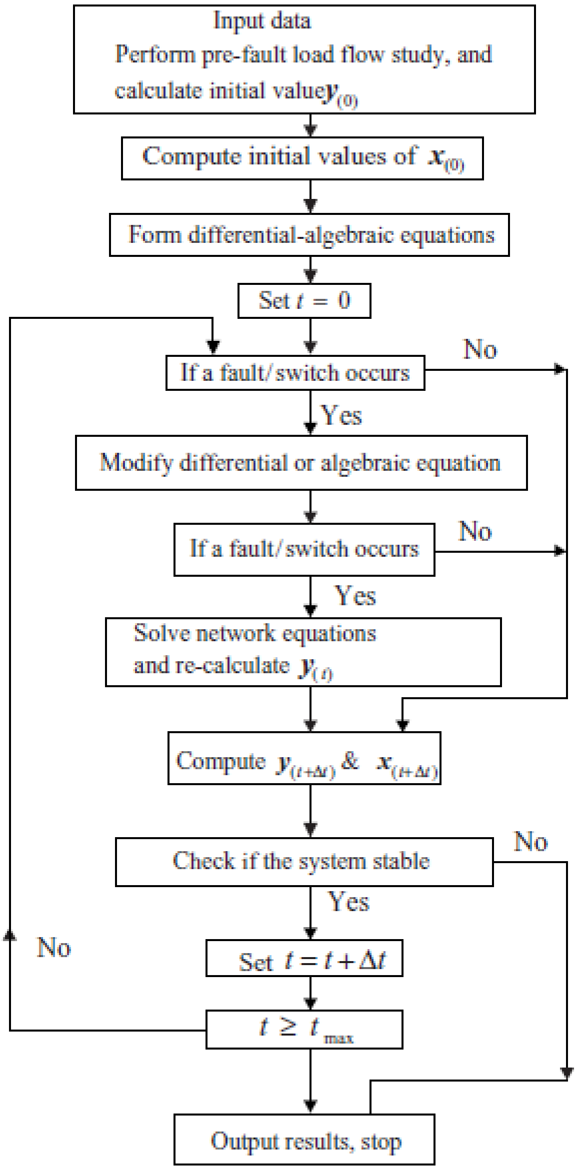

Figure E.1 Differential- algebraic Equations method applied to transient stability