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TRANSIENT STABILITY ENHANCEMENT IN POWER GENERATION SYSTEM USING INTERLINE POWER FLOW CONTROLLER

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FACULITY OF ELECTRICAL AND COMPUTER ENGINEERING

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BY

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BAHIR DAR, ETHIOPIA

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TRANSIENT STABILITY ENHANCEMENT IN POWER GENERATION SYSTEM USING INTERLINE POWER FLOW CONTROLLER (IPFC)

BY

BAYABLE AWOKE TARIKU

A thesis submitted to the school of Research and Graduate Studies of Bahir Dar Institute of Technology, BDU in partial fulfillment of the requirements for the degree of master in the Power System Engineering in the Faculty of Electrical and Computer Engineering.

Advisor:

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Bahir Dar, Ethiopia

August 3, 2020

DECLARATION

I, the undersigned, declare that the thesis comprises my own work. In compliance with internationally accepted practices, I have acknowledged and refereed all materials used in this work. I understand that non-adherence to the principles of academic honesty and integrity, misrepresentation/ fabrication of any idea/data/fact/source will constitute sufficient ground for disciplinary action by the University and can also evoke penal action from the sources which have not been properly cited or acknowledged.

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Date of submission: ________________

Place: Bahir Dar

This thesis has been submitted for examination with my approval as a university advisor.

Advisor Name: Dr.-Ing. Belachew Bantyrga

Advisor’s Signature: ______________________________

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ABSTRACT

In Ethiopia the power demand has been increasing rapidly, power generation and transmission are being affected due to limited resources, environmental restrictions and other losses. Transient stability control plays a vital role in maintaining the steady state operation of power system in the event of voltage, current and frequency deviation from normal operation due to fault occurrence, the major transient stability problems are coming due to sudden change in loads and, severe short circuit happened in transmission line. Flexible AC Transmission Systems (FACTS) are the power electronic components used to overcome the transient instability problems. So this thesis presents modelling and analysis of IPFC based on proportional integral (PI) controllers using MATLAB/ Simulink to improve the transient stability in Tis Abay power generation system. The study system is simulated using MATLAB-Simulink under steady state condition, three phases to ground fault and line to line fault condition with and without the application of IPFC. The simulation result shows for all the parameters such as the load angle improvement 70%, excitation voltage 70%, rotor speed 64%, active power 79% and reactive power 80% is by using IPFC.

Keyword: Transient stability, FACTS, Interline power flow controller, MATLAB/SIMULINK,

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LIST OF ABBREVIATIONS AND SYMBOLS

a. Abbreviations

AVR	Automatic Voltage Regulator
DPFC	Distributed Power Flow controller
EMTP	Electromagnetic Transient Program
FACTS	Flexible AC Transmission Systems
FC	Fixed Capacitor
HEPP	Hydroelectric Power Plant
HTG	Hydro Turbine Governor
HV	High Voltage
HVDC	High Voltage Direct Current
IPFC	Interline Power Flow Controller
MV	Medium Voltage
PI	Proportional Integral
PID	Proportional Integral and Derivative
PIM	Power Injection Model
PLL	Phase Locked Loop
p. u	Per Unit
PWM	Pulse Width Modulation
ref	Reference
RMS	Root Mean Square
SCT	Saturation Current Transformer
Se	Series
Sh	Shunt

S_N	Nominal apparent power
SSSC	Static Synchronous Series Compensator
STATCOM	Static Synchronous Compensator
SVC	Static VAR Compensator
SVS	Synchronous Voltage Source
TCR	Thyristor Controlled Reactor
TCSC	Thyristor Controlled Series Compensator
THD	Total Harmonic Distortion
T	Transformer
TSC	Thyristor Switching Capacitor
UPFC	Unified Power Flow Controller
VSM	Voltage Source Model

b. Symbols

3-ϕ	Three Phase
f	Fundamental frequency of power system
I	Current
Ki	Integral Constant
Kp	Proportional Constant
P	Real Power
Q	Reactive Power
S	Apparent Power
V	Voltage

CHAPTER ONE

1. INTRODUCTION

1.1. Background

An electrical power system is a complex interconnected network comprising of numerous generators, transmission lines, variety of loads and transformers. The term Flexible Alternating Current Transmission System (FACTS) devices describes a wide range of high voltage, large power electronic converters that can increase the flexibility of power systems to enhance AC system controllability, stability and increase power transfer capability. Demand for power and continuous development of the modern power system has led to an increasing complexity in the study of power systems, presenting new challenges to power system stability, and in particular, to the aspects of transient stability and small-signal stability [1]. Instabilities in power system are caused by insulation breakdown or collapse, long length of transmission lines, interconnected grid, changing system loads and other unpredicted disturbances in the system. These instabilities result in reduced line flows or even line trip. FACTS devices stabilize transmission systems with increased transfer capability and reduced risk of line trips. Other benefits attributed to FACTS devices are additional energy sales due to increased transmission capability, reduced wheeling charges due to increased transmission capability and due to delay in investment of high voltage transmission lines or even new power generation facilities. These devices stabilize transmission systems with increased transfer capability and reduced risk of line trips [1].

The major problem in power system is upholding steady acceptable system parameters like bus voltage, reactive power and active power under normal operating and abnormal conditions. This is usually system regulation problem and regaining synchronism after a major fault is critical for this phenomenon. Faults can cause loss of synchronism. As effects of instability, faults occur due to insulation breakdown or compromise as result of lightning ionizing air, power cables blowing together in the wind, animals or plants coming in contact with the wires, salt spray, pollution on insulators, system overloading, long transmission lines with uncontrolled buses at the receiving end, shortage of local reactive power, intrinsic factors, natural causes like harsh weather and small generation reserve margins. Such system disturbances have led to the introduction of FACTS devices such as SVC, SSSC, STATCOM, UPFC and IPFC [2, 3].

In stable power systems, when synchronous machines are disturbed, synchronism will either go back to their original state if there is no net change of power or will reach a new state without loss of synchronism and when there is net change in power; synchronism is lost [4]. Due to FACTS devices, the power can be flown through the chosen routes with consideration to mitigate the loss thereby averting losses due to system tripping or outages. UPFC and IPFC, for instance, are very versatile FACTS controllers. But IPFC is the latest FACTS device that can simultaneously manage and control the power flow of multiple lines. This capability has made this tool a distinct device and has many advantages. Given these properties, it also has the advantages of fine management and control in the system, as well as appropriate economic benefits for the owners of power transmission systems. IPFC is used in steady state to increase the capacity of lines power transfer, regulate and manage the power flow, compensate the reactive power, prevent the loop current and avoid the overload in the network. In addition to these capabilities, improvement of voltage stability, dynamic and transient stability correction as well as its application as power filter in distribution system have all made this tool into a multifunction device [5, 6].

A system can be unstable if it includes at least one unstable bus. Therefore, identifying the weak buses and areas is very important for power engineers to effectively plan and manage active and reactive resources, monitor and control voltage, so as to avoid transient instability. Several algorithms have been developed to detect a weak bus or area [3]. In power engineering, the power-flow study, or load-flow study, is a numerical analysis of the flow of electric power in an interconnected system. A power-flow study usually uses simplified notations such a one-line diagram and per-unit system and focuses on various aspects of AC power parameters, such as voltages, voltage angles, real power and reactive power. It analyzes the power systems in normal steady-state operation. The principal information obtained from the power-flow study is the magnitude and phase angle of the voltage at each bus, and the real and reactive power flowing in each line [7].

Back ground of case study area: The case study area for this thesis is Tis Abay II generation station. Tis Abay II Hydroelectric power plant (HEEP) is located about 30 km away from Bahir Dar city. Tis Abay II hydroelectric plant capable of turbine a discharge of $150m^3/s$ with an approximate gross head of 53m, with 73MW generated capacity producing a firm energy of 359 GWH yearly.

The power generated from Tis Abay II hydroelectric plant is transmitted to Bahir Dar substation using double circuit 132kV which is linked to the grid system of the country national grid.

The following single diagram shows Tis Abay generation station having two generators each 10.5kV generating voltage and 36 MW power rating with two transformers incorporated to step up the 10.5kV in to 132 kV of the outgoing line to Bahir Dar substation II.

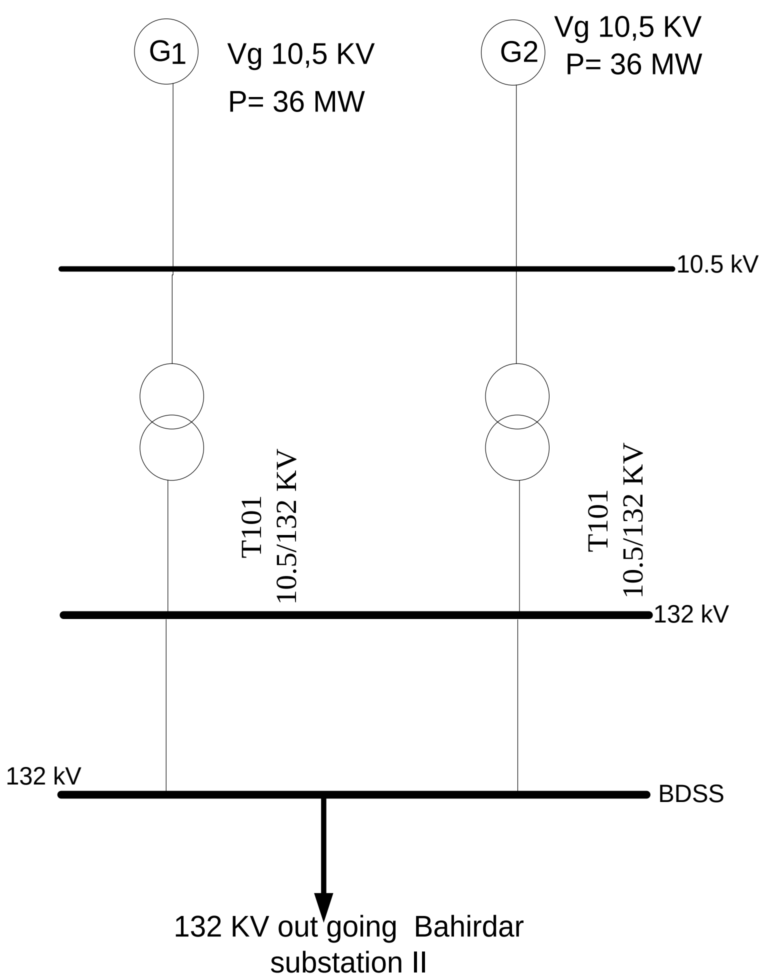

Figure 1-1: Single line diagram Tis Abay Generation Station

1.2. Problem Statements

Power system instability is the major problem in electrical power system. Disturbances, faults, loss of synchronism and sudden outage of a line in Tis Abay generation station are sometimes happened. Large disturbances such as a three-phase fault, short circuit transmission line faults, generator loading, and system loading cause transient instability to generating units. These circumstances cause power system problems. A transient instability problem is the most severe problem there. And also, continuous demand in electric power system network as well as heavy loading leads to system transient instability. Therefore FACTS device can be applied at these instances to overcome transient instability. In interconnected power systems, they enhance power networks via reactive, active and voltage control enabling the system to better transient stability and boost the loading capability of transmission lines to their rated thermal capabilities both in short term period and long term period. In this thesis the Interline Power Flow Controller (IPFC) is proposed to enhance the transient stability of Tis Abay generation station by providing fast response action during the fault.

1.3. Objectives

1.3.1. General Objective

The general objective of this thesis is to enhance the transient stability of Tis Abay power generation by using Interline power flow controller.

1.3.2. Specific Objective

- Data collection and analysis is performed.
- Develop and implement control system for IPFC on the MATLAB/ SIMULINK software which will make system stable quickly when fault is happening.
- Model the generation station system of Bahir Dar substation II
- Determine suitable location of interline power flow controller device.
- Analyse the extent of transient stability enhancement with and without IPFC FACT device.
- Apply Load flow analysis to know the performance of power and voltage at each bus.

1.4. Methodology

In order to complete this thesis, the thesis has been conducted based on the following steps.

- **Literature review:** a literature related to the improvement of transient stability a number of published ideas about transient stability, books; papers articles journals have been reviewed. In addition to that optimal allocation and sizing literature have been also reviewed.
- **Data Collection:** data have been collected from Tis Abay generation station. This data has been gathered by inspection and from recorded data some nameplate is read directly from the equipment.
- **Data analysis:** Collected data have been analysed and organized to make suitable for modelling and power flow analysis.
- **Studying Power Quality Problems:** studies about Transient stability and their improvement techniques.
- **Study and Modelling of IPFC**: The study about the IPFC method have been done to make sure the thesis is being successfully in the operating principle in order to understand the title of this thesis. Mathematical modelling and the controller strategy of IPFC with PI controller have been done.
- **Simulation**: the simulation has been carried out without the application of IPFC and with the application of IPFC based on PI controller due to 3-ϕ to ground fault and line to line fault conditions in Tis Abay generation station.

1.5. Significance of the Study

The main significances of this study are:

- Helps to damp the power oscillations that could damage the equipment.
- Control real and reactive power flow in the line independently.
- Reduction of system losses.
- Increment in the load-ability of lines to their thermal and voltage limits.
- Increase the transient stability, limiting short-circuits currents and overloads and hence making system more secure.

- Economic benefits for the owners of power transmission systems.
- Prevent blackout, improves generation productivity
- Guaranteeing system stability.
- Equalize active / reactive power between transmission lines.

1.6. Scope and Limitation of the Thesis

The thesis covers the use of Interline power flow controller to overcome the transient instability problem. It also covers the identification of the weakest bus. To develop dynamic power system models for the IPFC device. The modelling and simulations with and without inter line power flow controller are done in MATLAB/SIMULATION software.

Even though power system stability can be improved by different series and shunt FACT devices, like SVC and UPFC the scope of this thesis is limited to the study of transient stability improvement by interline power flow controller.

1.7. Literature Review

A historical review on the capable of supplying and absorbing real and reactive power techniques and device, to improve the transient stability using facts device, power flow analysis and to maintain synchronous operation of the machines when subjected to a large disturbance. Literature review of techniques used for improving the transient stability of the power system using facts devices are explained below.

In 2013 M.Karthik and P.Arul [3] , the SVC and Thyristor TSCS based FACTS device are employed to minimize the losses and improve power flow in long distance transmission line.

AM Parimi, NC Sahoo, I Elamvazuthi Automation, and Signal, 2011[8], Transient stability enhancement and power flow control in a multi-machine power system using interline power flow controller. In this paper, the non-linear dynamic model of a typical multi-machine power system incorporated with Interline Power Flow Controller (IPFC) has been developed. The oscillation modes with low damping ratio are identified from the Eigen value analysis of the linearised Phillips-Heffron model. A power oscillation damping controller has been designed for the IPFC using phase compensation technique to enhance the transient stability of the system. Additional power flow controllers have also been incorporated into the system.

In 2012 Dr. Tarlochan kaur and Sandeep kakran [9] this paper studies to improve the transient stability of long transmission line system by using SVC. In the present time power systems are being operated nearer to their stability limits due to economic and environmental reasons. Maintaining a stable and secure operation of a power system is a very important and challenging issue. Transient stability has given much attention by power system researches and planners in recent years and being regarded as one of major sources of power system insecurity. Series FACTS device has important role in improving the transient stability and increasing transmission capacity and damping low frequency oscillations. In this paper the shunt FACTS device SVC is used in a two area power system for improving the transient stability. MATLAB software is used.

In 2012 Carlo Cecati and Hamed Latafat,[10] study the transient stability of a two machine infinite bus system when affected by large disturbances by comparison of time domain approach versus transient energy function. Then decentralized non-linear controller is embedded within the power system and simulation results show that the transient stability has been greatly enhanced. Based on existing transient energy function of uncontrolled power system the controlled power system has been represented as a forced Hamiltonian system. The Lyapunov function is suitable for transient stability analysis of this controlled power system has been used for stability. Simulations in different operating points show the enhancement of transient stability of power system with controller in both time domain approach and energy function method.

In 2013 B .M. Naveen Kumar Reddy, Mr. G. V. Rajashekar, Dr. Himani Goyal [11] this paper is done by controlling and modulating power flow in transmission line using Static Synchronous Series Compensator (SSSC). Here, PWM techniques controlled for SSSC are conducted and control circuits are presented. In this paper SSSC is used to investigate effect of it in controlling active and reactive powers as well as damping power oscillations in the transient mode. SSSC equipped with source of energy in the DC link and can supply or absorb the reactive and active Power to or from the line. Simulations are done in MATLAB/Simulink environment.

Hague (2004) [12] has proposed a control strategy for the shunt FACTS devices to improve the first swing stability limit of a simple power system. It is shown that the speed based bang-bang control is unable to use the entire decelerating area in maintaining stability. The proposed control strategy improves the stability limit first by maximizing the decelerating area and then fully utilizing it in counter balancing the accelerating area.

Wang et al (2000) [13] have designed an optimal PI controller for the enhancement of transient stability of a single machine infinite bus power system with SVC using genetic algorithm approach. The application of this controller is concerned with the damping of oscillations of a synchronous generator as well as to control the system voltage.

May 2010 A. M. Parimi, I. Elamvazuthi, N. Saad [14] The IPFC provides simultaneous compensation for multiple transmission lines by real and reactive power flow control in the lines. It also provides voltage control, improves transient stability, and enhances oscillation damping. Recently; modelling of IPFC and its various control functions have undergone rigorous research. In the steady state model of IPFC with the power system is developed for load flow studies and power flow control. Control strategies with the help of supplementary PI proportional-integral) controller or lead-lag controller for damping enhancement are suggested. These controllers were designed based on linear models of single machine infinite bus (SMIB) power system installed with IPFC. However, studies on modelling of IPFC in a multi-machine power system for stability analysis are very limited.

In July 1999 L.Gyugyi, K.K.Sen, C.D.Schaud [6] present that Interline power flow controller (IPFC) is the latest generation of FACTS controllers. It is the combination of two or more SSSCs which are coupled via a common DC link. With this scheme, IPFC has the capability to provide an independently controllable reactive series compensation for each individual line and also to transfer real power between the compensated lines. There has been growing interest recently in studying the IPFC modelling, its basic function to control power flow among transmission lines and oscillation damping. Kazemi and Karimi proposed a PI supplementary damping controller for the IPFC for damping inter-area oscillations. However, the controller parameters are not optimized. Further, no effort had been made to identify the most suitable control parameter.

2006 Zhang Y, Zhang Yan, Chen C. [15] The UPFC combines the functions of the shunt and series compensation being capable to control the active and reactive power flows in the transmission line. This is an important achievement that can be used in power flow control, load sharing among parallel corridors, voltage regulation, and enhancement of transient stability and mitigation of system oscillations. The IPFC with two or more series connected converters working together is conceived for the compensation of multi-line transmission system. In this way, the power optimization of the overall system can be realized in the form of appropriate power transfer from overload to under loaded lines. This paper presents a new IPFC model with the aim of overcoming the problem of incorporating advanced power electronics regulating devices in classical power flow studies. The main characteristics of the proposed steady-state IPFC model are: the easy incorporation in existing load flow software, the presence of IPFC operating limits and automatic IPFC parameter calculation, which means that this model takes as input the desired (reference) active and reactive power flowing through the IPFC, and produces as output the correspondent IPFC parameters, which allow the desired power flow to be achieved.

In the above mentioned literature review to improve transient stability by using SVC, UPFC,TSCS compensate a single transmission line but in this thesis IPFC has two VSCs respectively connected in series with different lines, due to this it can address the problem of compensating real and reactive power flow controlling in multiple transmission lines at substations.

Others literature review presents about controller like PI, IP and Bang Bang for power system stability enhancement. So the main problem associated with the PI controller is that it is a linear controller, while all power electronics systems are non-linear system. This may raise a lot of control difficulties. It has also some disadvantages such as high starting overshoot, sensitivity to controller gains and sluggish response to sudden disturbance. In the Bang Bang controller the control signal is generated by two controllers for small and large disturbance. So it has a disadvantage in cost wise. In this thesis PI is chosen to balance the whole system and may compromise the transient response, such as settling time, overshoots, and oscillations.

1.8. Thesis Organization

The contents of the thesis have been divided into five chapters. A brief overview of each chapter is given as follows.

Chapter-1:

Chapter-2: this chapter discussed about theoretical background of Transient stability and basic concept of power system stability. In addition, deals about different types of FACTS devices and their basic structures. Basic structure, working principle and equivalent circuit of IPFC is also explained here in this chapter.

Chapter-3: deals with modelling of the power system i.e. modelling of synchronous generator, mathematical modelling of IPFC and control strategy of IPFC modelled with PI controller and generator excitation system was also explained.

Chapter-4: shows simulation results without and with IPFC is discussed. The active and reactive power, the rotor speed, the load angle, the stator current and the terminal voltage from the generator was measured for different conditions.

Chapter -5: The conclusions, recommendation, some suggestions for future work and Appendix are included in the final chapter.

CHAPTER TWO

2. THEORETICAL BACKGROUND OF TRANSIENT STABILITY AND FACT DEVICE

2.1. Introduction to Power System Stability

At present the demand for electricity is rising remarkably especially in developing country like Ethiopia. This persistent demand is leading to operation of the power system at its limit. The need for reliable, stable and quality power is on the rise due to electric power sensitive industries like information technology, communication, electronics etc. In this scenario, the electric power demand is not the only criteria but also it is the responsibility of the power system engineers to provide a stable and quality power to the consumers. These issues high light the necessity of understanding the power system stability. In this thesis we will try to understand how to improve the stability of a power system.

Power system stability has been recognized as an important problem for secure system operation since the 1920s. Many major blackouts caused by power system instability have illustrated the importance of this phenomenon. Historically, transient instability has been the dominant stability problem on most systems, and has been the focus of much of the industry's attention concerning system stability. As power systems have developed through continuing growth in interconnections, use of new technologies and controls, and the increased operation in highly stressed conditions, different forms of system instability have emerged. For example, voltage stability, frequency stability and inter area oscillations have become greater concerns than in the past. This has created a need to review the definition and classification of power system stability. A clear understanding of different types of instability and how they are interrelated is essential for the satisfactory design and operation of power systems. As well, consistent use of terminology is required for developing system design and operating criteria, standard analytical tools, and study procedures[16].

Stability of an electric power system is thus a property of the system motion around an equilibrium set, i.e., the initial operating condition. In an equilibrium set, the various opposing forces that exist in the system are equal instantaneously (as in the case of equilibrium points) or over a cycle (as in the case of slow cyclical variations due to continuous small fluctuations in loads or periodic attractors). Power systems are subjected to a wide range of disturbances, small and large. Small disturbances in the form of load changes occur continually; the system must be able to adjust to the changing conditions and operate satisfactorily. It must also be able to survive numerous disturbances of a severe nature, such as a short circuit on a transmission line or loss of a large generator. A large disturbance may lead to structural changes due to the isolation of the faulted elements.

The actions of automatic controls and possibly human operators will eventually restore the system to normal state. On the other hand, if the system is unstable, it will result in a run-away or run-down situation; for example, a progressive increase in angular separation of generator rotors, or a progressive decrease in bus voltages. An unstable system condition could lead to cascading outages and a shut-down of a major portion of the power system. Power systems are continually experiencing fluctuations of small magnitudes. However, for assessing stability when subjected to a specified disturbance, it is usually valid to assume that the system is initially in a true steady-state operating condition.

The classification of power system stability proposed here is based on the following considerations[16]:

- The physical nature of the resulting mode of instability as indicated by the main system variable in which instability can be observed.
- The size of the disturbance considered which influences the method of calculation and prediction of stability.
- The devices, processes, and the time span that must be taken into consideration in order to assess stability.

2.2. Basic Concepts and Definitions of Power System Stability

Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most of the system variables bounded so that practically the entire system remains un broken [17]. The disturbances mentioned in the definition could be faults, load changes, generator outages, line outages, voltage collapse or some combination of these. Power system stability can be broadly classified in to rotor angle, voltage and frequency stability. Each of these three stabilities can be further classified in to large disturbance or small disturbance, short term or long term. The classification is shown in Fig.1.1.

2.2.1 Rotor angle stability

It is the ability of the system to remain in synchronism when subjected to a disturbance. The rotor angle of a generator depends on the balance between the electromagnetic torque due to the generator electrical power output and mechanical torque due to the input mechanical power through a prime mover remaining in synchronism means that all the generators electromagnetic torque is exactly equal to the mechanical torque in the opposite direction. If in a generator the balance between electromagnetic and mechanical torque is disturbed, due to disturbances in the system, then this will lead to oscillations in the rotor angle. Rotor angle stability is further classified in to small disturbance angle stability and large disturbance angle stability.

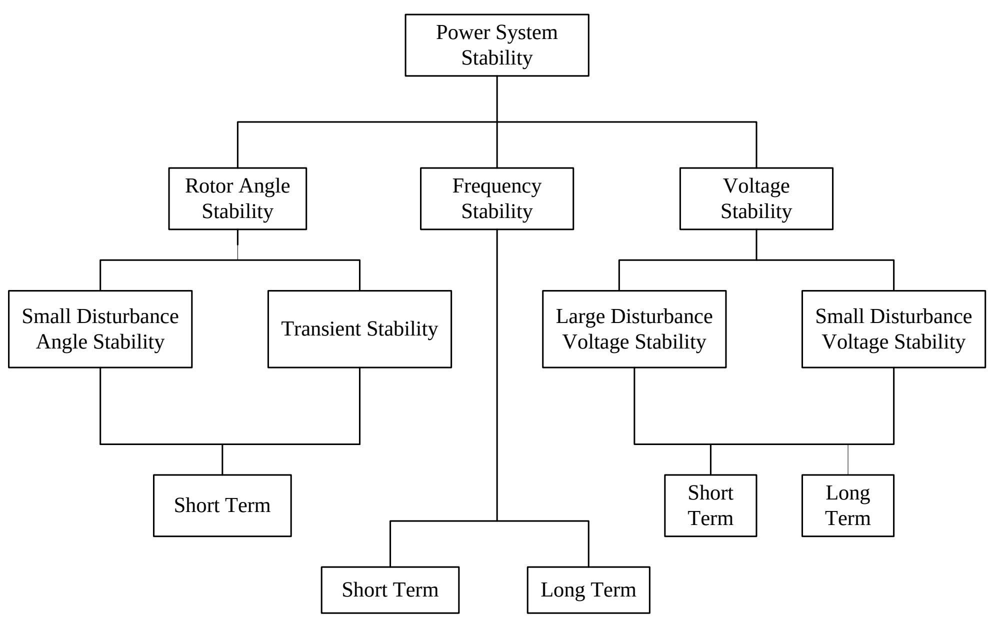

Figure 2-1: Classification of power system stability

2.2.2 Small-disturbance or small-signal angle stability

It is the ability of the system to remain in synchronism when subjected to small disturbances. If a disturbance is small enough so that the non-linear power system can be approximated by a linear system, then the study of rotor angle stability of that particular is called as small disturbance angle stability analysis. Small disturbance can be small load changes like switching on or off of small loads, line tripping, small generators tripping etc. Due to small disturbances there can be two types of instabilities: non oscillatory instability and oscillatory instability. In non-oscillatory instability the rotor angle of a generator keeps on increasing due to a small disturbance and in-case of oscillatory instability the rotor angle oscillates with increasing magnitude.

2.2.3 Large-disturbance or transient angle stability

It is the ability of the system to remain in synchronism when subjected to large disturbances. Large disturbances can be faults, switching on or off of large loads, large generator stripping etc. When power system is subjected to large disturbance, it will lead to large excursions of generator rotor angles. Since there are large rotor angle changes the power system cannot be approximated by a linear representation like in the case of small-disturbance stability. The time domain of interest in case of large-disturbances well as small-disturbance angle stability is anywhere between 0.1-10s. Due to this reason small and large-disturbance angle stability are considered to be short term phenomenon. It has to be noted here that though in some literature “dynamic stability” is used in place of transient stability, according to IEEE task force committee report [18], only transient stability has to be used.

2.2.4 Voltage stability

Voltage stability refers to the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition. It depends on the ability to maintain/restore equilibrium between load demand and load supply from the power system. The problem is usually the voltage drop that occurs when active power and reactive power flow through inductive reactance associated with the transmission network. A criterion for voltage stability is that, at a given operating condition for every bus in the system, the bus voltage magnitude increases as the reactive power injection at the same bus is increased. A system is voltage unstable if, for at least one bus in the system, the bus voltage magnitude (V) decreases as the reactive power injection (Q) at the same bus is increased. Instability that may result occurs in the form of a progressive fall or rise of voltages of some buses. A possible outcome of voltage instability is loss of load in an area, or tripping of transmission lines and other elements by their protective systems leading to cascading outages. Loss of synchronism of some generators may result from these outages or from operating conditions that interrupt field current limit.

As in the case of rotor angle stability, it is useful to classify voltage stability into the following subcategories:-

Large disturbance voltage stability: refers to the system's ability to maintain steady voltages following large disturbances such as system faults, loss of generation, or circuit contingencies.

Small disturbance voltage stability: refers to the system's ability to maintain steady voltages when subjected to small perturbations such as incremental changes in system load. This form stability is influenced by the characteristics of loads, continuous controls, and discrete controls at a given instant of time. This concept is useful in determining at any instant how the system voltages will respond to small system changes. With appropriate assumptions, system equations can be linearised for analysis thereby allowing computation of valuable sensitivity information useful in identifying factors influencing stability.

Voltage stability may be either a short term or a long term phenomenon.

Short term voltage stability: involves dynamics of fast acting load components such as induction motors, electronically controlled loads, and HVDC converters.

Long term voltage stability: involves slower acting equipment such as tap-changing transformers, thermostatically controlled loads, and generator current limiters. Basis for distribution between voltage stability and angle stability is that voltage stability depends on the balance of reactive power demand and generation in the system where as the angle stability mainly depends on the balance between real power generation and demand.

It is the ability of the system to maintain steady state voltages at all the system buses when subjected to a disturbance. It depends on the ability to maintain/restore equilibrium between load demand and load supply from the power system. A possible outcome of voltage instability is loss of load in an area, or tripping of transmission lines and other elements by their protective systems leading to cascading outages. Loss of synchronism of some generators may result from these outages or from operating conditions that disturb field current limit. If the disturbance is large, then it is called as large-disturbance voltage stability and if the disturbance is small, it is called as small-disturbance voltage stability. Unlike angle stability, voltage stability can also be a long term phenomenon. In case voltage fluctuations occur due to fast acting devices like induction motors, power electronic drive, HVDC etc. then the time frame for understanding the stability is in the range of 10-20s and hence can be treated as short term phenomenon. On the other hand if voltages variations are due to slow change in load, over loading of lines, generator shifting reactive power limits, tap changing transformer set then time frame for voltage stability can stretch from 1 minute to several minutes.

The main difference between voltage stability and angle stability is that voltage stability depends on the balance of reactive power demand and generation in the system where as the angle stability mainly depends on the balance between real power generation and demand.

2.2.5 Frequency stability

It refers to the ability of a power system to maintain steady frequency following a severe disturbance between generation and load. It depends on the ability to restore equilibrium between system generation and load, with minimum loss of load. Frequency instability may lead to sustained frequency swings leading to tripping of generating units or loads. During frequency outings, the characteristic times of the processes and devices that a re-energized will range from fraction of seconds like under frequency control to several minutes, corresponding to the response of devices such as prime mover and hence frequency stability may be a short-term phenomenon or a long-term phenomenon.

Accordingly power system stability problems are classified into three basic types.

- ✓ Steady State
- ✓ Dynamic and
- ✓ Transient.

Steady state stability is the ability of the system to develop restoring forces equal to or greater than the disturbing force and remain in equilibrium or synchronism after small and slow disturbances. Increase in load is a kind of disturbance. Further, there may be sudden disturbances due to sudden change of load, Switching operation, Loss of generation, Fault.

Dynamic stability is the ability of the power system to maintain stability under continuous small disturbances also known as small signal stability. These small disturbances occur due to random fluctuations in loads and generation levels. Furthermore this stability is able to regain synchronism with addition of automatic control devices such as automatic voltage regulator (AVR) and frequency controls.

Transient stability is the ability of the power system to maintain synchronism when subjected to a severe transient disturbance or is the ability of the power system to maintain in stability after large, major and sudden disturbances such as the occurrence of a fault, the unexpected outage of a line or removal of loads. Each generator operates at the same synchronous speed and frequency of 50 hertz while a slight balance between the input mechanical power and output electrical power is maintained. Whenever generation is less than the actual consumer load, the system frequency falls. On the other hand, whenever the generation is more than the actual load, the system frequency rise. The generation is also interconnected with each other and with the loads they supply via high voltage transmission line [19].

2.3 Fact devices

Flexible AC Transmission System (FACTS) according to IEEE is defined as, Alternating current transmission systems incorporating power electronic-based and other static Controllers to enhance controllability and increase power transfer capability [20]. FACTS devices have been proposed for effective power flow control and regulating bus voltage in electrical power systems, thus resulting in an increased transfer capability, low system losses and improved stability. FACTS devices give facilities to the controllers that are able to control the interconnected parameters, which govern the operation of transmission systems including series and shunt impedance, current, voltage, phase angle and the damping oscillations at various frequencies below the rated frequency. FACTS-devices contains more advanced technology of voltage source converters based today mainly on Insulated Gate Bipolar Transistors (IGBT) or Insulated Gate Commutated Thyristors (IGCT). Voltage Source Converters provide a free controllable voltage in magnitude and phase due to a pulse width modulation of the IGBTs or IGCTs. There are various types of FACTS devices and classified as follows.

- Series FACTS Controllers
- Shunt FACTS Controllers
- Combined Series-Shunt FACTS Controllers
- Combined Series-Series FACTS Controllers

2.3.1 Series FACTS Controllers

These FACTS Controllers are injecting the voltage in series with the connected line, if this series injected voltage is in phase quadrature to the line current, the series controller simply delivers or receives the variable reactive power. Other than the quadrature with injected voltage and line current the controller can involve itself for real power control. These FACTS controllers works by injecting a successive tension (i.e. variable impedance multiplied by the current that flows through it) in quadrature with the line current. A series controller may consist of a variable electronics based source at the fundamental frequency or variable impedance such as a capacitor or reactor. Provided the voltage is in phase quadrature with the line current, a serial controller only supplies or consumes reactive power, hence; any other phase angle only represents active power management. Members of this type of controller include SSSC, and TCSC.

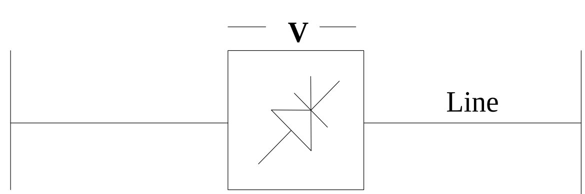

Figure 2-2: Representation of Series FACTS Controller.

Thyristor Controlled Series Capacitor (TCSC)

TCSC is one of the most important and best known FACTS devices, which has been in use for many years to increase the power transfer as well as to enhance system stability. The main circuit of a TCSC is shown in Fig. 2.3. The TCSC consists of three main components: capacitor bank C, bypass inductor L and bidirectional thyristors SCR1 and SCR2. The firing angles of the thyristors are controlled to adjust the TCSC reactance in accordance with a system control algorithm, normally in response to some system parameter variations. According to the variation of the thyristor firing angle or conduction angle, this process can be modelled as a fast switch between corresponding reactance's offered to the power system [21].

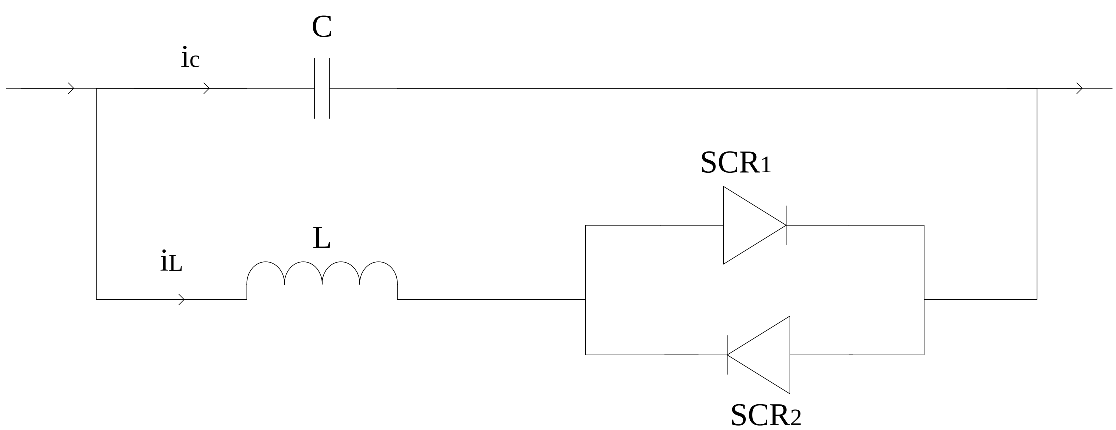

Figure 2-3: Thyristor controlled series capacitor

Static Synchronous Series Compensator (SSSC)

SSSC is a solid-state Voltage Sourced Converter (VSC), which generates a controllable AC voltage connected in series to power transmission lines in a power system. SSSC compensates virtually transmission line impedance by injecting controllable voltage (VS) in series with the transmission line. Voltage source are in quadrature with the line current, and to compute more in an inductive or a capacitive reactance so as to influence the power flow in the transmission lines. The virtual reactance inserted by V influences electric power flow in the transmission lines independent of the magnitude of the line Current. The variation of V is performed by means of a VSC connected on the secondary side of a coupling transformer. A capacitor connected on the DC side of the VSC acts as a DC voltage source. To keep the capacitor charged and to provide transformer and VSC losses, a small active power is drawn from the line. VSC uses IGBT-based PWM inverters. The machine speed is determined by the machine

Inertia constant and by the difference between the mechanical torque, resulting from the applied mechanical power, and the internal electromagnetic torque and so the responses are obtained considering the inertia. Further, the gate limits are also considered in the analysis. VSC using IGBT-based Pulse Width Modulation (PWM) inverters is used in the present study. The details of the inverter and harmonics are not represented in power system stability studies; a GTO-based model can also be used. This type of inverter uses PWM technique to synthesize a sinusoidal waveform from a DC voltage with a typical chopping frequency of a few kilohertz. Harmonics are cancelled by connecting filters at the AC side of the VSC. This type of VSC uses a fixed DC voltage VDC Converter voltage VC is varied by changing the modulation index of the PWM modulator. SSSC circuit diagram is illustrated in fig 2.4. The controllable parameter of this device is the magnitude of the series voltage source VS. This voltage source is regulated by a PID Controller. This controller is used for constant power flow through the line[22].

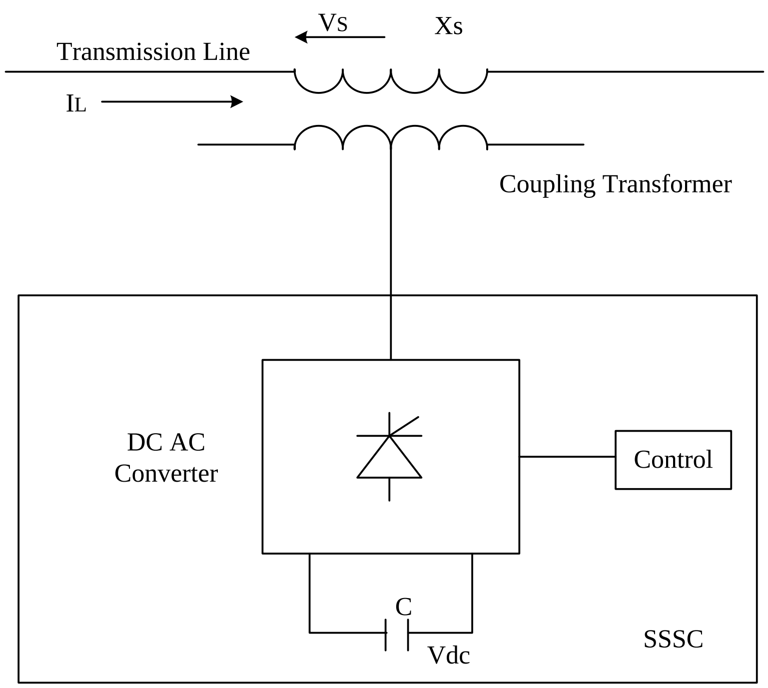

Figure 2-4: Voltage source model of SSS

2.3.2 Shunt FACTS Controllers

The shunt FACTS Controllers may be variable impedance type i.e. reactor or capacitor adjustable source based on the power electronics, which is shunt connected to the line in order to inject variable current. Here up to which the current is injected to the line voltage with phase quadrature it deliveries or absorbs the variable reactive power to the system, other than that at any angle for voltage and current it well work for the real power flow [23].

Static VAR Compensator (SVC)

Static VAR Compensator (SVC) is a first generation FACTS device that can control voltage at the required bus thereby improving the voltage profile of the system. The primary task of an SVC is to maintain the voltage at a particular bus by means of reactive power compensation (obtained by varying the firing angle of the thyristors). SVCs have been used for high performance steady state and transient voltage control compared with classical shunt compensation. SVCs are also used to dampen power swings, improve transient stability, and reduce system losses by optimized reactive power control[24].

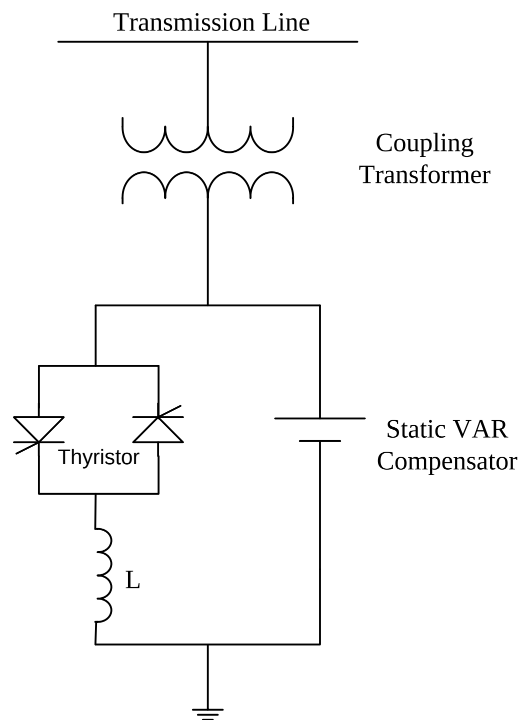

Figure 2-5: Configuration of SVC

Static Synchronous Compensator (STATCOM)**:-**In 1976, Gyugyi proposed the concept of STATCOM mainly based on current sourced or voltage sourced converter. According to IEEE STATCOM is a static synchronous generator operated as a shunt-connected static VAR compensator whose capacitive or inductive output current can be controlled independent of the

AC system voltage, STATCOM does not require passive elements like inductors and capacitors. STATCOM's are mainly used in transmission and distribution network for better power quality and for power system stabilization, STATCOM provides dynamic voltage support in transmission and distribution network. STATCOM also act as active filter to absorb harmonics in the system. STATCOM is shunt-connected voltage, or current sources convertor based VAR generator and Static VAR compensator is thyristor-controlled reactor and thyristor switched capacitor. The overall performance of STATCOM is better and greater flexibility than SVC[25]. Basic structure for STATCOM is illustrated in the Figure 2.6

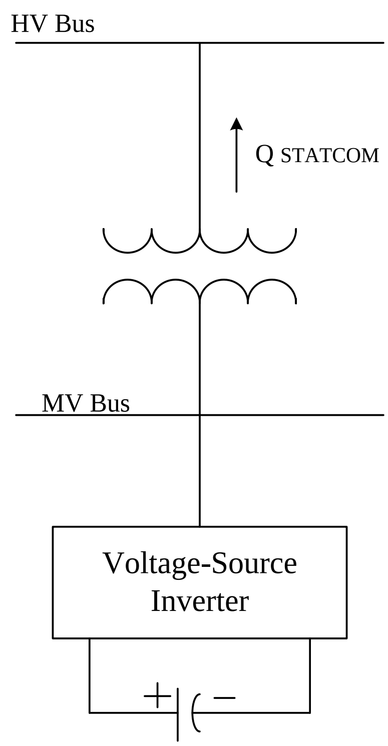

Figure 2-6: Static synchronous compensator

STATCOM is Voltage-Source Inverter (VSI), which converts a DC input voltage into AC output voltage in order to achieve the active and reactive power that needed by the system. STATCOM is a shunt-connected controller device that adjusts the voltage and the angle of internal voltage source to control the voltage at the connected bus to the reference values. STATCOM shows constant current characteristics when the voltage is low/high under/over the limit. This allows the devices to delivers constant reactive power at the limits compared to SVC. From the power system dynamic stability viewpoint, the STATCOM provides better damping characteristics than the SVC as it is able to transiently exchange active power with the system [26].

Thyristor Controlled Reactor (TCR): is a shunt connected, thyristor controlled inductor whose effective reactance is varied in continuous manner by partial conductor control of the thyristor valve. TCR is a subset of SVC in which conduction time and hence, current in a shunt reactor is controlled by a thyristor-based AC switch with firing angle control [27]. Output is adjusted to exchange capacitive or inductive current. It is used to Maintain or control specific parameters of the electrical power system (typically bus voltage).

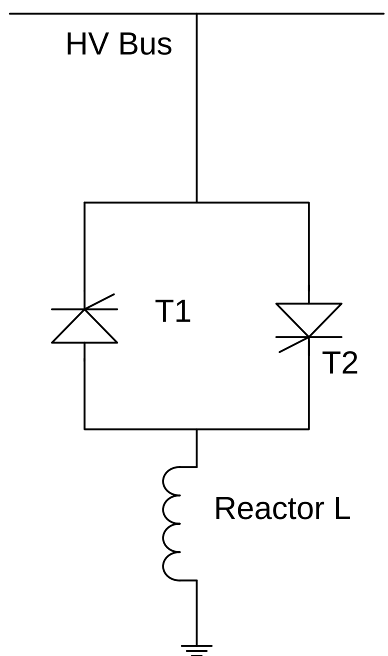

Figure 2-7: Thyristor controlled reactor

2.3.3 Combined Series-Series FACTS Controllers

These could be a combination of separate series controllers. The configuration of Combined Series-Series FACTS Controllers provides independent series reactive power compensation for each line but also transfers real power among the lines via power link. The presence of power link between series controllers names this configuration as Unified Series-Series Controller [23]. The real power transfer capability of the Unified Series-Series Controller referred to as Inter Line Power Flow Controller and used to balance both the real and reactive power flow in the lines. A Serial-Serial FACTS Controller is a combination of well-coordinated serial controllers in a multi-line transmission system. It is just a unified controller, in which the serial controllers provide reactive compensation for each line, thereby transferring active power between the lines via a power link. Active and reactive power balance is achieved either by the line feeder controller or through the transmission capacity of the active power that presents a unified serial controller. The unified nature therefore enables it to achieve active power transfer between each other by proper connection of the dc terminals of the converters of the controllers. A typical example of serial-serial controller is Interline Power Flow Controller (IPFC) [28].

Interline Power Flow Controller (IPFC) consists of two (or more) series voltage source converter-based devices (SSSCs) installed in two (or more) lines and connected at their DC terminals. Thus, in addition to serially compensate the reactive power, each SSSC can provide real power to the common DC link from its own line. The IPFC gives them the possibility to solve the problem of controlling different transmission lines at a determined substation. In fact, the under-utilized lines make available an excess power which can be used by other lines for real power control. This capability makes it possible to equalize both real and reactive power flow between the lines, to transfer power demand from overloaded to under-loaded lines, to compensate against resistive line voltage drops and the corresponding reactive line power, and to increase the effectiveness of a compensating system for dynamic disturbances (transient stability and power oscillation damping). Therefore, the IPFC provides a highly effective scheme for power transmission at a multi-line substation. The IPFC is a multi-line FACTS device.

2.4 Basic Structure of Interline power flow controller (IPFC)

An Interline Power Flow Controller (IPFC) consists of a set of converters that are connected in series with different transmission lines. The schematic diagram of IPFC is illustrated in Figure 2.8. The converters are connected through a common DC link to exchange active power. Each series converter can provide independent reactive compensation of its own transmission line. [36].

The IPFC structure makes it possible to exchange reactive power, which is among the capabilities of every SSSC as well as to exchange active power with the line. This active power can be obtained via power exchange through DC connection between the SSSCs in different lines. On the other hand, the transmitted powers in each line is a function of the voltage amplitude of sending and receiving buses, phase shift of sending and receiving buses, and series impedance of the line. IPFC can directly or indirectly impact on each of these factors, and increase the power transfer[37].

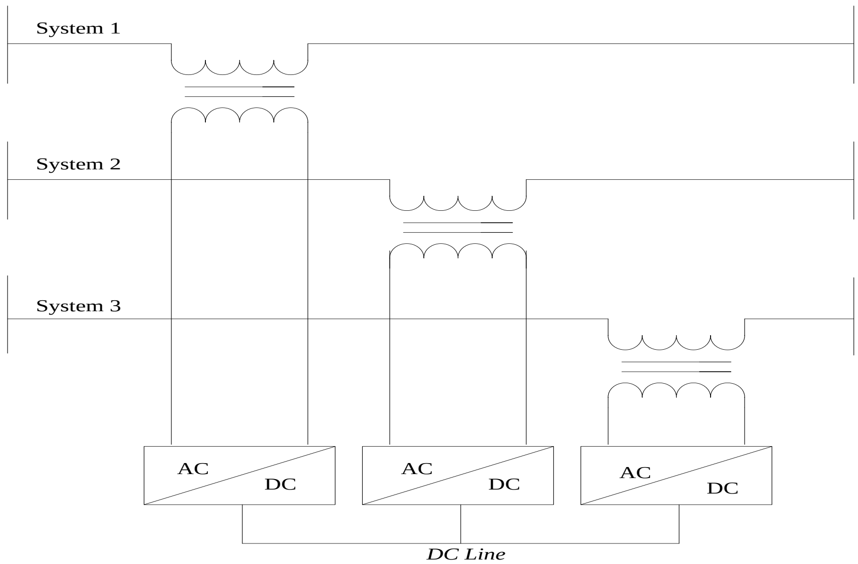

Figure 2-8 Schematic diagram of IPFC converter

In its general form the interline power flow controller employs number of DC to AC inverters each providing series compensation for a different line as shown in the above figure 2.8. IPFC is designed as a power flow controller with two or more independently controllable static synchronous series compensator's (SSSC) which are solid state voltage source converters injecting an almost sinusoidal voltage at variable magnitude and are linked via a common DC capacitor[38].

As mentioned above IPFC consist a set of converters. The converters are connected through a common DC link to exchange active power. Each series converter can supply independent reactive compensation of its own transmission line [23].

2.4.1 Working principle of interline power flow controller (IPFC)

Operating Principle of IPFC in its general form the inter line power flow controller employs a number of AC to DC converters each providing series compensation for a different line. In other words, the IPFC comprises a number of Static Synchronous Series Compensator's (SSSC). The simplest IPFC consist of two back-to-back ac to dc converters, which are connected in series with two transmission lines through series coupling transformers and the dc terminals of the converters are connected together via a common dc link as shown in Fig. 2.8.With this IPFC, in addition to providing series reactive compensation, any converter can be controlled to supply real power to the common dc link from its own transmission line [39].

The IPFC structure makes it possible to transfer reactive power, as well as to exchange real power with the line. This active power can be obtained through power exchange through DC connection between the SSSCs in different lines. On the other hand, the transmitted powers in each line is a function of the voltage amplitude of sending and receiving buses, phase shift of sending and receiving buses and series impedance of the line.

The interline power flow controller works with a number of alternative current to direct current converters each providing series compensation for a different transmission line. To explain briefly let use two back-to-back voltage-source converters (VSCs) based on the use of gate-turnoff (GTO) thyristor valves. The voltage source converters (VSC) produce voltages that vary in magnitude and phase angle. These voltages are inserted in series with the managed transmission lines using series transformers.

The real power exchanged at the ac terminal is converted by the corresponding VSC into dc power which appears at the dc link as a negative or a positive demand. Consequently, the real power negotiated by each VSC must be equal to the real power negotiated by the other VSC through the dc lines. As result interline power flow controller (IPFC) can maintain the flow of active and reactive power in multiple line system even when a failure occurs [28].

2.4.2 Equivalent Circuit of IPFC

An elementary IPFC consisting of two VSCs is illustrated in Fig. 2.9. Its equivalent circuit and the corresponding vector diagram are shown in Fig. 2.10 and Fig. 2.11 respectively. Each inverter can compensate a transmission line by series voltage injection and the common DC link is represented by a bi-directional link for active power exchange between the two voltage sources[40].

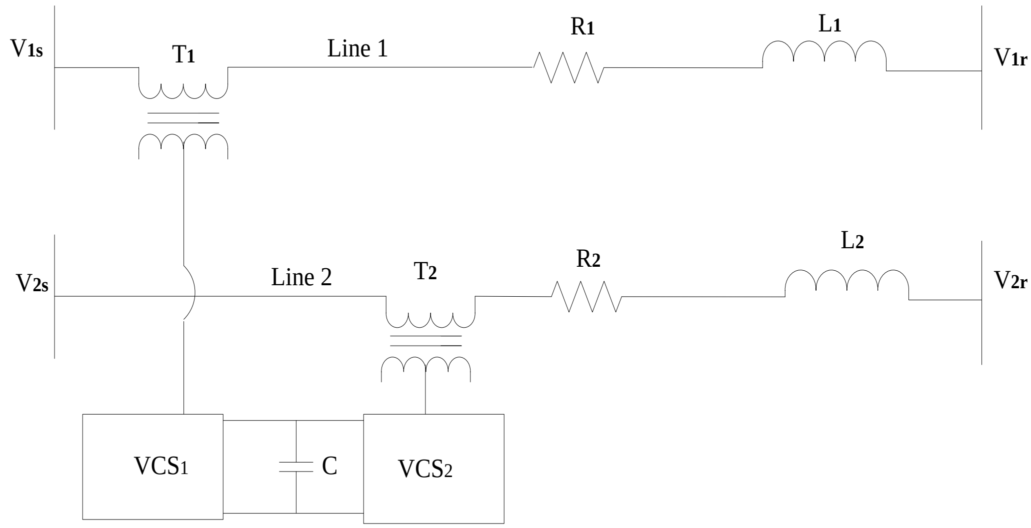

Figure 2-9: IPFC with two voltage source converter

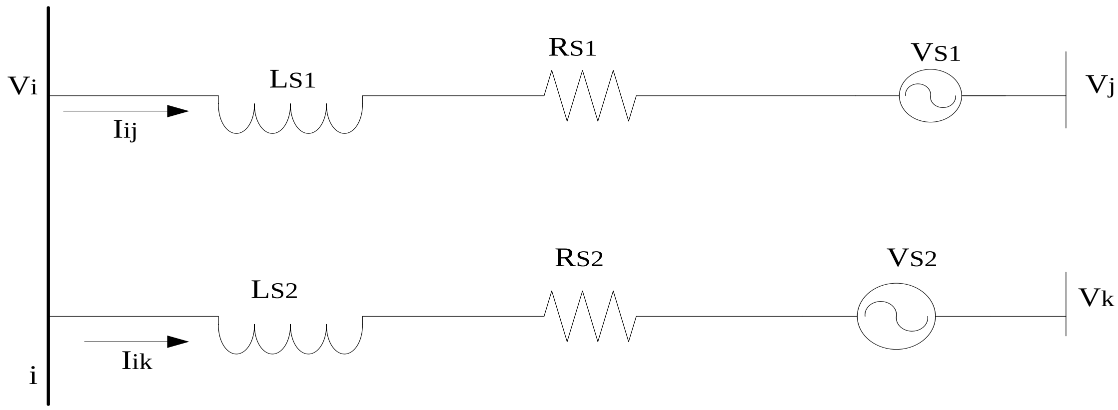

Figure 2-10: Equivalent circuit

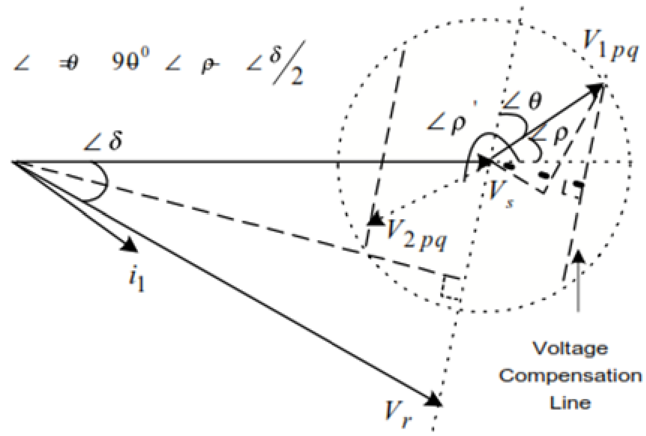

Figure 2-11: Vector diagram

2.5 Combined Shunt-Series FACTS Controllers

These are arrangement of shunt and series controller and they are connected in such way that control of both in synchronized manner. The real or active power exchange is take place through the power dc link when these controllers are connected to each other and also with the line [29]. As the name implies, this controller is a coordinated combination of separate shunt and series controllers. They work by injecting current into the system with the shunt part of the controller and voltage in series in the line with the series part of the controller. Thus the shunt and series part of the controllers are unified, in which case, real power exchange between the series and shunt controllers can be achieved via a proper link. Members of this class of controllers include UPFC and DPFC [30].

Unified Power Flow Controller (UPFC)

Fig. 2.12 show a combination of static synchronous compensator (STATCOM) and a static series compensator (SSSC) which are coupled via a common dc link, to allow bidirectional flow of real power between the series output terminals of the SSSC and the shunt output terminals of the STATCOM, and are controlled to provide concurrent real and reactive series line compensation without an external electric energy source. The UPFC, by means of angularly unconstrained series voltage injection, is able to control, concurrently or selectively, the transmission line voltage, impedance, and angle or, alternatively, the real and reactive power flow in the line. The UPFC may also provide independently controllable shunt reactive compensation. A unified power flow controller (UPFC) is the most promising device in the FACTS concept. Either it has the ability to adjust the three control parameters, i.e. the transmission line reactance and bus voltage, and phase angle between two buses, simultaneously or independently[31].

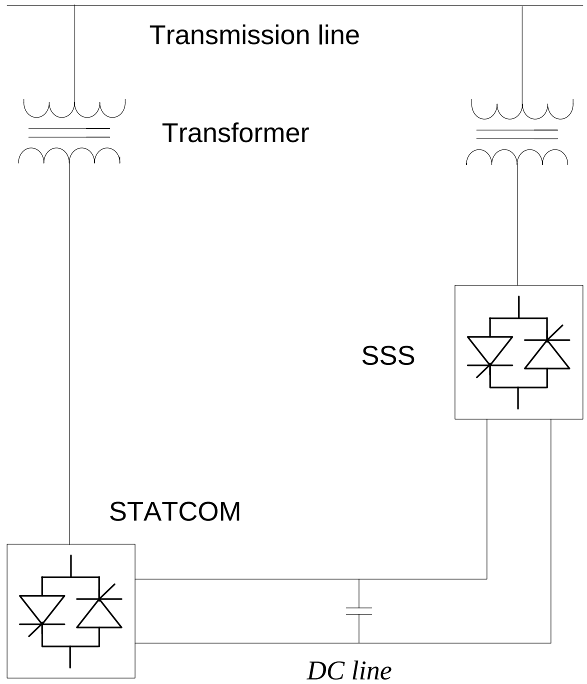

Figure 2-12: Unified power flow controller

Distributed Power Flow Controller (DPFC) - DPFC structure is derived from the Unified power flow controller (UPFC) structure by elimination of the common DC link and distribution of the series converter of UPFC. Similar as the UPFC, the DPFC consists of shunt converter and several small independent series converters. The shunt converter is similar to the STATCOM (Static Compensator) while the series converter employs the D-FACTS (Distribution flexible alternating-current transmission system concept), which is to use multiple single-phase converters instead of one three-phase [32, 33]. Within the DPFC, the transmission line is used as a connection between shunt converter output and AC port of series converters, instead of using DC-link for power exchange between converters. The method of power exchange in DPFC is based on power theory of non-sinusoidal components. Non-sinusoidal voltage and current can be presented as the sum of sinusoidal components at different frequencies [34, 35]. The DPFC (Distributed power flow controller) has the same capability as UPFC (unified power flow controller) to balance the line parameters, i.e., line impedance, transmission angle, and bus voltage magnitude [32, 33]. A basic structure of DPFC is as shown in figure 2.13.

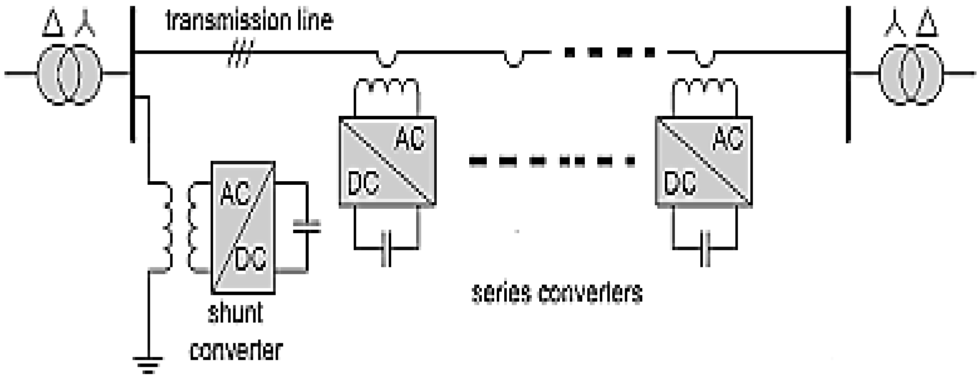

Figure 2-13: DPFC Configuration

CHAPTER THREE

3. SYSTEM MODELLING

This chapter of the thesis presents the fundamental model of hydro turbine, synchronous generator, and excitation system of the power generation system.

3.1. Hydro Turbine modelling

Hydro generating stations consists of a reservoir, gate to release water to generating station, pen-stock (a conduit) to carry water from the reservoir up to the hydro turbine. The turbine can be impulse-type (Pelton wheel) or reaction turbine (Francis or propeller). In this study the hydro turbine of Tis Abay II is Francis turbine type. This turbine head is 53m. The water which flows from the reservoir through the pen-stock is directed on to the turbine blades. The blades of a Francis turbine are carefully shaped to extract the maximum amount of energy from the water flowing through it. The hydro turbine and the rotor of the synchronous machine are mounted on the same shaft. The three basic mathematical equation and modelling hydro turbine of Francis at Tis Abay are [18]:

- Velocity of water in the penstock
- Turbine mechanical power
- Acceleration of water column

The velocity of the water in the penstock is given by:

$$\boldsymbol{U = K_U G\sqrt{H}} \qquad \textbf{3.1}$$

where:-

U = water velocity

G = gate position

H = hydraulic head at gate

K_U = a constant of proportionality

A small devation of normalized water velocity

$$\Delta\overline{\boldsymbol{U}} = \frac{\mathbf{1}}{\mathbf{2}}\,\Delta\overline{\boldsymbol{H}} + \Delta\overline{\boldsymbol{G}} \qquad \textbf{3.2}$$

The turbine mechanical power is proportinal to the product of pressure and flow

$$\boldsymbol{P_m = K_p H U} \qquad \textbf{3.3}$$

A small derivation of normalized mechanical power

$$\Delta\overline{P_m} = \Delta\overline{H} + \Delta\overline{U} \qquad 3.4$$

Substituting delta U:

$$\Delta\overline{P}_m = 1.5\Delta\overline{H} + \Delta\overline{G} \qquad 3.5$$

Substituting delta H:

$$\Delta\overline{P}_m = 3\Delta\overline{U} - 2\Delta\overline{G} \qquad 3.6$$

The acceleration of water column due to a change in head at the turbine characterized by Newton's second low of motion may be expressed as:

$$(\rho LA)\frac{d\Delta U}{dt} = -A(\rho\alpha_G)\Delta H \qquad 3.7$$

Where

L= length of conduit

A= pipe area

ρ= mass density

α_g= acceleration due to gravity

ρLA= mass of water in the conduit

$\rho\alpha_g\Delta H$= incremental change in pressure at turbine gate

t= time in seconds

The acceleration equation in normalized form:

Dividing both sides by $A\rho\alpha_g H_O U_O$ We get $\frac{LU_O}{\alpha_g H_O}\frac{d}{dt}\left(\frac{\Delta U}{U_O}\right) = -\frac{\Delta H}{H_O}$

$$T_W\frac{d\Delta U}{dt} = -\Delta\overline{H} \qquad T_w = \frac{LU_O}{\alpha_g H_O} \qquad 3.8$$

T_w - water starting time.

It is the time required for a head Ho to accelerate the water in the penstock from standstill to the velocity U_O.

$T_w \approx$ 0.5s to 4.0s (at full load)

$$\Delta\overline{U} = \frac{1}{2}\Delta\overline{H} + \Delta\overline{G} \qquad T_w\frac{d\Delta\overline{\overline{U}}}{dt} = -\Delta\overline{H} \qquad 3.9$$

$$T_w\frac{d\Delta\overline{U}}{dt} = 2(\Delta\overline{G} - \Delta\overline{U} \qquad 3.10$$

$$\boldsymbol{T_w s \Delta \bar{U} = 2(\Delta \bar{G} - \Delta \bar{U}}$$ **3.11**

$$\Delta \bar{U} = \frac{1}{1+\frac{1}{2}T_w s}\Delta \bar{G}$$ **3.12**

Substituting from $\Delta\bar{U}$ from $\Delta\bar{P}_m = 3\Delta\bar{U} - 2\Delta\bar{G}$

And rearrenging we get:-

$$\frac{\Delta\bar{\bar{P}}_m}{\Delta\bar{G}} = \frac{1-T_W S}{1+\frac{1}{2}T_W S}$$ **3.13**

The equation 3-1 representing the transfer functions of a hydraulic turbine.

The turbine can be modelled as a first order lag as shown Fig. 3.1.

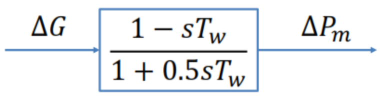

Figure 3-1: Turbine model

3.2. Model of synchronous generator

Synchronous generators are most commonly constructed with a three-phase armature winding on the stator (although other poly-phone arrangements are also found) and an excitation winding (known as the field winding) on the rotor. In addition, synchronous generator rotors include other conducting paths in which currents can be induced during a transient. In some cases, these conducting paths are deliberately included by the designer; e.g., pole-face damper windings. In other cases, they are inherent to the machine design, such as in the case of the currents which can be induced in the rotor body of a solid-rotor turbo generator. Early on in the process of developing techniques for the analysis of synchronous machines, it was recognized that analyses can be greatly simplified if they are performed in a reference frame rotating with the rotor. For such analyses, the armature currents and voltages are transformed into two sets of orthogonal variables, one set aligned with the magnetic axis of the field winding, known as the rotor direct axis (d-axis), and a second set aligned along the rotor at a position 90 electrical degrees from the field-winding magnetic axis. This second axis is known as the rotor quadrature axis (q-axis)[49].

According to the arrangement of the field and armature windings, synchronous machines may be classified as rotating-armature type or rotating –field type.

Rotating-Armature Type: The armature winding is on the rotor and the field system is on the stator (dc generator).

Rotating –Field type: the armature winding is on the stator and the field system is on the rotor (synchronous generator). Since commutator is not required in an alternator, it is usually more convenient and advantageous to place the field winding on the rotating part and armature winding on the stationary part as shown in figure 3.2.

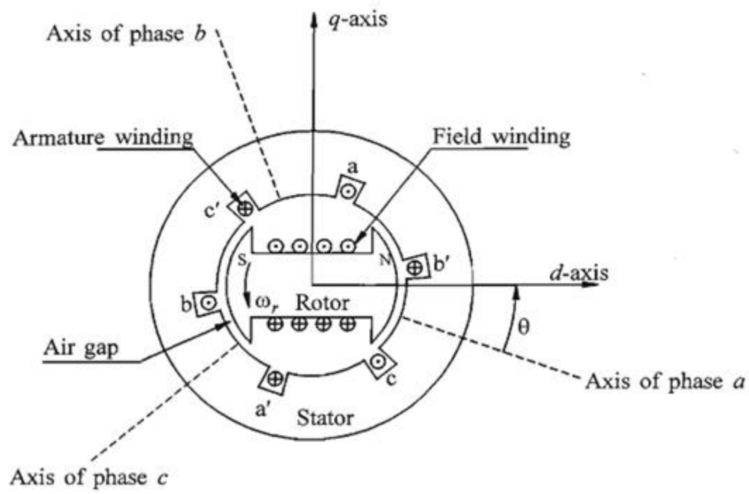

Figure 3-2: Schematic diagram of Synchronous generator

Here the main parts of synchronous generator are:

- Rotor windings or field windings
- Stator windings or Armature windings

3.2.1. Armature and field structure

The armature windings usually operate at a voltage that is significantly higher than that of the field and thus they require more space for insulation. The three phase windings of the armature are distributed 120^0 electrical apart in space so that, with uniform rotation of the magnetic field, voltages displaced by 120^0 in time phase will be produced in the windings. Because the armature is subjected to a varying magnetic flux, the stator iron is built up of thin laminations to reduce eddy current losses. When carrying balanced three phase currents, the armature will produce a magnetic field in the air gap rotating at synchronous speed. The field produced by the direct current in the rotor winding. On the other hand, revolves with the rotor.

The synchronous speed is given by:

$N_s = \frac{120f}{P}$

Where N_s is the speed in revolution per minute, f is the frequency in Hz and P is the number of field poles[16].

3.2.2. Synchronous generator model in ABC reference frame

As a standard practice, the magnetic axis of the field winding is defined as the rotor direct axis (d-axis), and another axis at a position of 90 electrical degrees from the field winding magnetic axis is defined as the rotor quadrature axis (q-axis).

Based on the reference direction defined in Figure 3.3 below, the generator flux current relationship can be written in the form of;

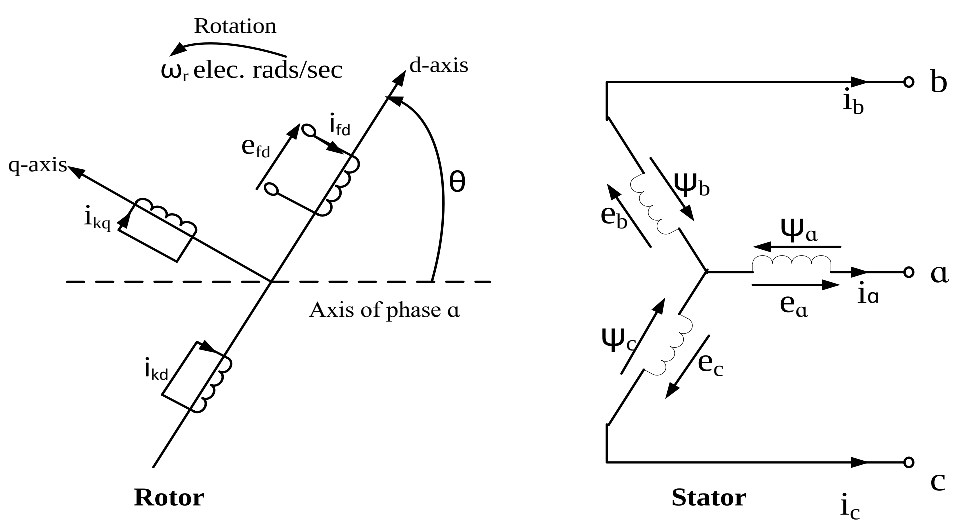

Figure 3-3: Stator and rotor circuits of synchronous machine

where a, b and c are stator phase winding Fd if field winding, kd and kq are d-q axis amortisseur (damper winding) circuit, k= 1, 2…n, n= number of amortisseur circuits

$$\begin{bmatrix} \psi_{abcs} \\ \psi_{dqr} \end{bmatrix} = \begin{vmatrix} L_s & L_{sT} \\ L_{sr}^T & L_r \end{vmatrix} \begin{bmatrix} -i_{abcs} \\ i_{dqr} \end{bmatrix} \quad \textbf{3.14}$$

where, $\psi_{abcs} = [\psi_a \psi_b \psi_c]^T$; is the 3-phase stator winding flux linkage vector,

$\psi_{dqr} = \left[\psi_{fd}\,\psi_{1d}\,\psi_{1q}\;\;\psi_{2q}\;\right]^T$; is the rotor winding flux linkage vector,

$i_{abcs} = [i_a\, i_b\, i_c]^T$; is the 3-phase stator winding current vector,

$i_{dqr} = [i_{fd}\, i_{1d}\, i_{1q}\;\; i_{2q}\;]^T$; is the rotor winding current vector, the stator winding inductance matrix is,

$$\mathbf{L_s} \quad \mathbf{L_s} = \begin{bmatrix} \mathbf{L_{aa}} & \mathbf{L_{ab}} & \mathbf{L_{ac}} \\ \mathbf{L_{ba}} & \mathbf{L_{bb}} & \mathbf{L_{bc}} \\ \mathbf{L_{ca}} & \mathbf{L_{cb}} & \mathbf{L_{cc}} \end{bmatrix} \qquad \mathbf{3.15}$$

Where, phase a, phase b, phase c self-inductance is given by

$$Laa = Laao + Laa_2Cos2\theta$$
$$L_{bb} = Laao + Laa_2Cos2\theta\left(\theta - \frac{2\pi}{3}\right)$$
$$Lcc = Laao + Laa_2Cos2\theta\left(\theta + \frac{2\pi}{3}\right) \qquad \mathbf{3.16}$$

Again phase ab, phase ac, and phase bc mutual inductances are mathematically

$$L_{ab} = L_{ba} = -L_{abo} + L_{ab2}Cos\left(2\theta + \frac{\pi}{3}\right)$$
$$L_{ac} = L_{ca} = -L_{abo} + L_{ab2}Cos\left(2\theta - \frac{\pi}{3}\right)$$
$$L_{bc} = L_{cb} = -L_{abo} + L_{ab2}Cos\left(2\theta - \pi\right) \qquad \mathbf{3.17}$$

Where, Θ is the electrical angle between the magnetic axis of the phase α and the magnetic axis of the field winding. The rotor winding inductance matrix,

$$L_r = \begin{bmatrix} L_{ffd} & L_{f1d} & 0 & 0 \\ L_{1d} & L_{11d} & 0 & 0 \\ 0 & 0 & L_{11q} & L_{12q} \\ 0 & 0 & L_{12q} & L_{22q} \end{bmatrix} \qquad \mathbf{3.18}$$

Where L_{ffd} is self-inductance of the field winding, L_{11d}, L_{11q} and L_{22q} are self- inductance of the damper windings at the d-axis and the q-axis respectively and L_{f1d} is the mutual inductances between the field winding and the damper winding in the d-axis, and also L_{12q} is the mutual inductances between two damper windings in the q-axis.

The mutual inductances between stator and rotor windings are given by:

$$Lsr = \begin{bmatrix} L_{afd}Cos\theta & L_{a1d}Cos\theta & -L_{a1q}Sin\theta & -L_{a2q}Sin\theta \\ L_{afd}Cos\left(\theta-\frac{2\pi}{3}\right) & L_{a1d}Cos\left(\theta-\frac{2\pi}{3}\right) & -L_{a1q}Sin\left(\theta-\frac{2\pi}{3}\right) & -L_{a2q}Sin\left(\theta-\frac{2\pi}{3}\right) \\ L_{afd}Cos\left(\theta+\frac{2\pi}{3}\right) & L_{a1d}Cos\left(\theta+\frac{2\pi}{3}\right) & -L_{a1q}Sin\left(\theta+\frac{2\pi}{3}\right) & -L_{a2q}Sin\left(\theta+\frac{2\pi}{3}\right) \end{bmatrix} \qquad \textbf{3.19}$$

where, L_{afd}, L_{a1d}, L_{a1q} and L_{a2q} are the peak mutual inductances between the stator winding and rotor windings.

The generator terminal voltages can be written as;

$$\begin{bmatrix} e_{abcs} \\ e_{dqr} \end{bmatrix} = \begin{bmatrix} R_S & O \\ 0 & R_r \end{bmatrix} + p\begin{bmatrix} \psi_{abcs} \\ \psi_{dqr} \end{bmatrix} \qquad \textbf{3.20}$$

Where *P* is differential operator *d/dt*,

$e_{abcs} = [e_a \quad e_b \quad e_c]^T$ Is the three-phase stator winding voltage vector, and

$e_{dqr} = [e_{fd} \quad 0 \quad 0 \quad 0]^T$, is the rotor winding voltage vector with the short-circuited damper windings,

$R_S = diag[R_a \quad R_a \quad R_a]$ and $R_r = diag[R_{fd} \quad R_{1d} \quad R_{1q} \quad R_{2q}]$, is the three phase stator and rotor winding resistance matrix respectively.

However as shown in Figure 3.3 the stator winding inductances *L* and the mutual inductances L_{sr} between the stator and the field winding are varying with the rotor position θ, and therefore varying parameter makes the computation of the generator phase model difficult. On the other hand, the computation can be greatly simplified if the generator model can be expressed in a reference frame rotating with respect to the rotor.

3.2.3 Generator model in dq0 reference frame

One set aligns with the d-axis defined along the magnetic axis of the generator field winding, and the other set aligns with the q-axis defined at 90 electrical degrees from the d-axis. This transformation is known as the Park's *dq0* transformation. The following matrices can be used for the transformation.

$$P = \sqrt{\frac{2}{3}}\begin{bmatrix} Cos\theta & Cos\left(\theta - \frac{2\pi}{3}\right) & Cos\left(\theta + \frac{2\pi}{3}\right) \\ -Sin\theta & -Sin\left(\theta - \frac{2\pi}{3}\right) & -Sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}, \qquad 3.21$$

And the inverse transformation (from *dq* to *abc* reference frame) is

$$P^{-1} = \sqrt{\frac{2}{3}}\begin{bmatrix} Cos\theta & -Sin\theta & \frac{1}{\sqrt{2}} \\ Cos\left(\theta - \frac{2\pi}{3}\right) & -Sin\left(\theta - \frac{2\pi}{3}\right) & \frac{1}{\sqrt{2}} \\ Cos\left(\theta + \frac{2\pi}{3}\right) & -Sin\left(\theta + \frac{2\pi}{3}\right) & \frac{1}{\sqrt{2}} \end{bmatrix} \qquad 3.22$$

The coefficients of the matrices are particularly chosen to make the expression of the generator electrical output to be power invariant for both *abc* phase variables and *dqo* variables. This simplifies the generator per-unit model, to be shown in the next section, for the design of the excitation control. The *abc* phase variables of the stator flux linkage, voltage and current in *dqo* variables as follows:

$$\varphi\ \mathrm{dqos} = \mathrm{p}\varphi\mathrm{abcs}$$

$$\mathrm{e_{dqos}} = \mathrm{p^{e}_{abcs}}$$

$$\mathrm{i_{dqos}} = \mathrm{p^{i}_{abcs}} \qquad 3.23$$

Where $\psi_{dqos} = [\Psi_d \quad \Psi_q \quad \Psi_o]^T$ is the dqo stator flux linkage vector,

$e_{dqos} = [e_d \quad e_q \quad e_o]^T$ is the dqo stator voltage vector,

$i_{dqos} = [i_d \quad i_q \quad i_o]^T$ is the dqo stator current vector,

Similarly, the flux-current relationship can be expressed in *dqo* variables:

$$\begin{bmatrix} \Psi_{dqos} \\ \Psi_{dqr} \end{bmatrix} = \begin{bmatrix} PL_S P^{-1} & PL_{sr} \\ L_{sr}^T P^{-1} & L_r \end{bmatrix}\begin{bmatrix} -i_{dqos} \\ i_{dqr} \end{bmatrix} \qquad 3.24$$

Where,

$$PL_{Sr} = \sqrt{\frac{2}{3}}\begin{bmatrix} L_{afd} & L_{a1d} & 0 & 0 \\ 0 & 0 & -L_{a1q} & -L_{a2q} \\ 0 & 0 & 0 & 0 \end{bmatrix}, L_{sr}^{T}P^{-1} = \sqrt{\frac{2}{3}}\begin{bmatrix} L_{afd} & 0 & 0 \\ L_{a1d} & 0 & 0 \\ 0 & -L_{a1q} & 0 \\ 0 & -L_{a2q} & 0 \end{bmatrix} \quad \textbf{3.25}$$

$PL_S P^{-1}$ = diag $[\mathrm{L}_d \quad \mathrm{L}_q \quad \mathrm{L}_0]$

$\mathrm{L}_d = \mathrm{L}_{aa0} + \mathrm{L}_{ab0} + 3\mathrm{L}_{aa2}/2 \qquad \mathrm{L}_d = \mathrm{L}_1 + \mathrm{L}_{ad}$

$\mathrm{L}_q = \mathrm{L}_{aa0} + \mathrm{L}_{ab0} - 3\mathrm{L}_{aa2}/2 \qquad \mathrm{L}_q = \mathrm{L}_1 + \mathrm{L}_{aq}$

$\mathrm{L}_q = \mathrm{L}_{aa0} - 2\mathrm{L}_{ab0}$

Where L_d, L_q and L_0 are commonly defined as the d-axis inductance, q-axis inductance and zero-sequence inductance respectively. L_1 is the leakage inductance, and L_{ad} and L_{aq} are the mutual inductances associated with the air- gap leakage flux linkages due to i_d and i_q respectively.

Similarly, with the dq0 transformation, the stator voltage equation becomes,

$$e_{dqos} = -i_{dqos}R_s + \mathrm{Pp}\,(P^{-1}\psi_{dqos}) = -i_{dqos}R_s + pP^{-1}\psi_{dqos} + p(pP^{-1})\psi_{dqos} \quad \textbf{3.26}$$

$$= -i_{dqos}R_s + \mathrm{p}\psi_{dqos} + \omega_r[\psi_q \quad \psi_d \quad 0]^T$$

$$= -i_{dqos}R_s + \mathrm{p}\Psi_{dqos} + \omega_r[\Psi_q \quad \Psi_d \quad 0]^T$$

Where, $\omega_r = \frac{d\theta}{dt} = 2\pi f$ electrical rad/s. this equation is expressed in detail as follows,

$$\begin{bmatrix} e_d \\ e_q \\ e_0 \\ e_{fd} \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_a & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & R_a & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & R_a & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & R_{fd} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & R_{1d} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & R_{1q} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & R_{2q} \end{bmatrix} \begin{bmatrix} -i_d \\ -i_q \\ -i_0 \\ i_{fd} \\ i_{1d} \\ i_{1q} \\ i_{2q} \end{bmatrix} + p \begin{bmatrix} \psi_d \\ \psi_q \\ \psi_0 \\ \psi_{fd} \\ \psi_{1d} \\ \psi_{1q} \\ \psi_{2q} \end{bmatrix} + \omega_r \begin{bmatrix} \psi_q \\ \psi_q \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad \textbf{3.27}$$

The zero sequence components can be eliminated for the stability of a power system with balanced circuits, and the components of $p\psi$/dq0s which is small and decays fast in post-disturbance can also be eliminated to simplify the analysis of the generator stability and the design of the generator control. This leads to the following equation.

$$e_d = -R_a i_d - \omega_r \psi_q \quad \textbf{3.28}$$

$$e_q = -R_a i_q + \omega_r \psi_d \quad \textbf{3.29}$$

where, ω_r is the generator rotor speed in electrical radians per second. The three-phase generator terminal power can be calculated from the terminal voltages and currents as below:

$$P_t = e_a i_a + e_b i_b + e_c i_c$$

$$\mathbf{P_t} = e_d i_d + e_q i_q$$

3.30

The internal electromagnetic power P_e produced by the generator can be obtained from the generator terminal power plus the losses on the stator winding resistance, and can be expressed in terms of flux linkages:

$$P_e = P_t + \left(i_d^2 + i_q^2\right) = \omega_r (\psi_d i_q - \psi_q i_d) \quad \textbf{3.31}$$

And the electric torque can be obtained:

$$T_e = \frac{P_e}{w_{mech}} = \frac{w_r (\Psi(\Psi d i_q - \Psi_q i_d)}{w_{mech}} = \frac{n_p (\Psi_d i_q - \Psi_q i_d)}{2} \quad \textbf{3.32}$$

where, ω_{mech} is the rotor speed in mechanical radians per second, and n_p is the number of poles.

$$Ns = \frac{120f}{p}$$

Therefore, the speed of a rotating magnetic field is proportional to the frequency of the three phase excitation currents, which generates the field. The generator terminal voltage and equivalent network voltage in *dq* reference can be expressed as,

$$V_t = e_d + je_q \quad \textbf{3.33}$$

$$V_E = e_{Bd} + je_{B_q} \quad \textbf{3.34}$$

Where, $e_d = V_t sin\delta_i$

$e_q = V_t cos\delta_i$ are the dq components of V_t

$e_{Bd} = V_E Sin\delta_E$

$e_{Bq} = V_E Cos\delta_E$ are the dq components of V_E

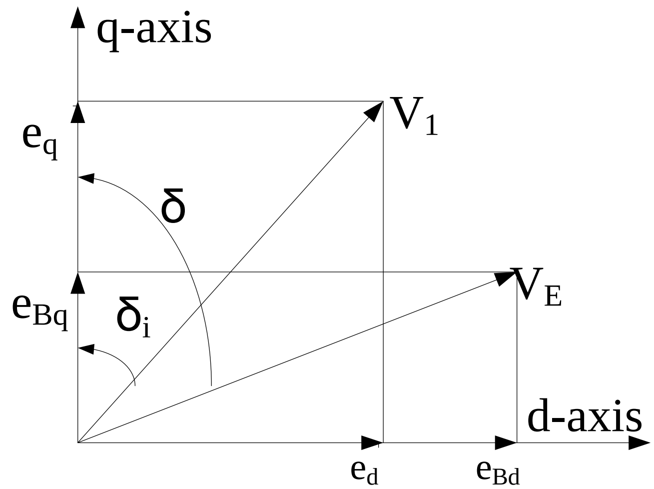

Figure 3-4: Phasor diagram of a generator connected to a power system network

The voltage and current are related as follows,

$$V_t = V_e + (R_E + jX_E)jI_t \quad \textbf{3.35}$$

Where,

$I_t = i_d + ji_q$, is the generator terminal current in terms of d.

$\begin{cases} e_d = e_{Bd} + R_E\, i_d - X_E i_q \\ e_q = e_{Bq} + R_E\, i_q + X_E i_d \end{cases}$, are the dq components of V, in terms of circuit components

Three phase complex power at the generator terminal is

$$S_{3\phi} = 3VI_a{*} \quad \textbf{3.36}$$

Also

$$I_a = \frac{|E||\delta - V||O^2|}{|Z_s|\beta} \quad \textbf{3.37}$$

Then

$$S_{3\phi} = 3\ \frac{|E||V|}{|Z_s|}(\ \llcorner\beta - \ \llcorner\delta) - 3\frac{|V|^2}{|Z_s|}\ \llcorner\beta \quad \textbf{3.38}$$

Three phase real and reactive powers are:

$$P_{3\phi} = 3\ \frac{|E||V|}{|Z_s|} cos(\beta - \delta) - 3\frac{|V|^2}{|Z_s|} cos\beta \quad \textbf{3.39}$$

$Q_{3\phi} = 3\ \frac{|E||V|}{|Z_s|} sin(\beta - \delta) - 3\frac{|V|^2}{|Z_s|} sin\beta$ **3.40**

If r_a is neglected, then $Z_s = jx_s$ and $\beta = 90^0$,

Therefore,

$P_{3\phi} = 3\ \frac{|E||V|}{|X_s|} \sin\delta$ **3.41**

$Q_{3\phi} = 3\ \frac{|E||V|}{|x_s|} \cos\delta - |V|$ **3.42**

Voltage induced is dependent upon flux and speed of rotation, hence from what we have learnt so far, the induced voltage can be found as follows:

$E_a = \sqrt{2}\pi\ NC\phi f$ **3.43**

For simplicity, it may be simplified to as follows

E_a =k E_a =kϕω **3.44**

K= $\frac{N_c P}{\sqrt{2}}$ (if ω in electrical rad/s), K= $\frac{N_c P}{2\sqrt{2}}$ (if ω in mechanical rad/s)

Generally, when a synchronous machine is operated as a generator, a prime mover is required to drive the generator. In steady state, the mechanical torque of the prime mover should balance with the electromagnetic torque produced by the generator and the mechanical loss torque due to friction and wind age, or

T_{pm} =T + T_{loss}

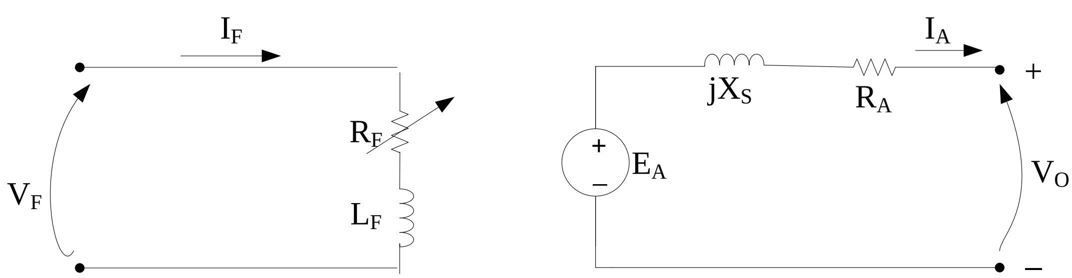

Figure 3-5: Equivalent circuit of synchronous generator

Multiplying the synchronous speed ω_{syn} to both sides of the torque equation, we have the power balance equation as

$P_{pm} = P_{em} + P_{loss}$

Where $P_{pm} = T_{pm}\,\omega_{syn}$ is the mechanical power supplied by the prime mover, $P_{em} = T\omega_{syn}$ the electromagnetic power of the generator, and $P_{loss} = T_{loss}\,\omega_{syn}$ the mechanical power loss of the system. The electromagnetic power is the power being converted into the electrical power in the three phase stator windings. That is

$$P_{pm} = T\omega_{syn} = 3E_a I_a cos\phi_{E_a I_a} \qquad \textbf{3.45}$$

Where $\phi_{E_a I_a}$ is the angle between phasor, E_a and I_a.

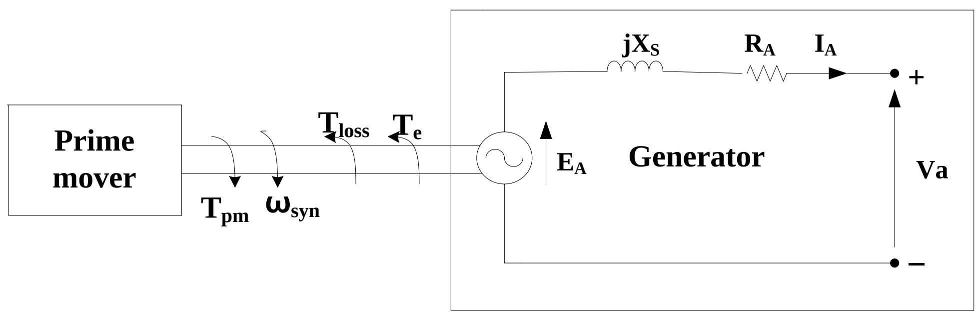

Figure 3-6: Synchronous machine operated as generator

For larger synchronous generators, the winding resistance is generally much smaller than the synchronous reactance, and thus the per phase circuit equation can be approximately written as

$V_a = E_a + jX_s I_a$

The corresponding phasor diagram is

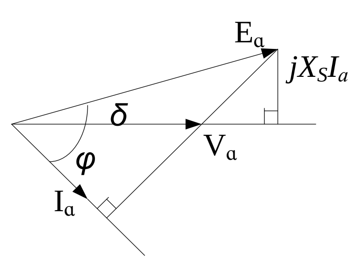

Figure 3-7: Phasor diagrams of synchronous generator armature winding

From the phasor diagram, we can readily obtain,

$$V_a sin\delta = X_s I_a cos\phi \quad \textbf{3.46}$$

When the phase winding resistance is ignored, the output electrical power equals the electromagnetic power, or

$$P_{em} = P_{out} = 3V_a I_a cos\phi \quad \textbf{3.47}$$

Therefore,

$$P_{em} = \frac{3E_a I_a}{X_s} sin\delta \quad \textbf{3.48}$$

And

$$T = \frac{P_{em}}{\omega_{syn}} = \frac{3E_a I_a}{\omega_{syn} X_s} sin\delta \quad \textbf{3.49}$$

Where δ is the angle between the phasor of the voltage and the *emf*, Known as the load angle. When the stator winding resistance is ignored can also be regarded as the angle between the rotor and stator rotating magnetic fields.

3.3 Excitation Systems

Excitation systems are one of the most important parts of the synchronous generators. Excitation system of the generator comprise from machines, devices and appliances that are intended to provide direct current to the generator field winding and this current regulation and to regulate generator voltage and reactive power output. Additionally, excitation systems are also responsible for control and protection functions of the power system. The control functions include the control of voltage and reactive power flow, and the enhancement of the system stability. The protective functions ensure that the capability limits of the synchronous machine, excitation system, and other are not exceeded.

3.3.1 Excitation System Requirements

The performance requirements of the excitation system are determined by considerations of the synchronous generator as well as the power system.

Generator considerations: The basic requirements are that the excitation system supply and automatically adjust the field current of the synchronous generator to maintain the terminal voltage as the output varies with in its continuous capability of the generator. In addition, the excitation system must be able to respond to transient disturbances with field forcing consistent with the generator instantaneous and short term capabilities. The generator capabilities in this regard are limited by several factors: rotor insulation failure due to high field voltage, rotor heating due to high field current, stator heating due to high VAR loading, and heating due to excess flux (volts/Hz).

Power system considerations: From the power system view point, the excitation system should contribute to effective control of system voltage and improvement (enhancement) of system stability. It should be capable of responding rapidly to a disturbance as to improve transient stability, and of modulating the generator field currents as to enhance small signal stability.

3.3.2. Elements of Excitation Systems

Figure 3.8 shows the functional block diagram of a typical excitation control system for large synchronous generator.

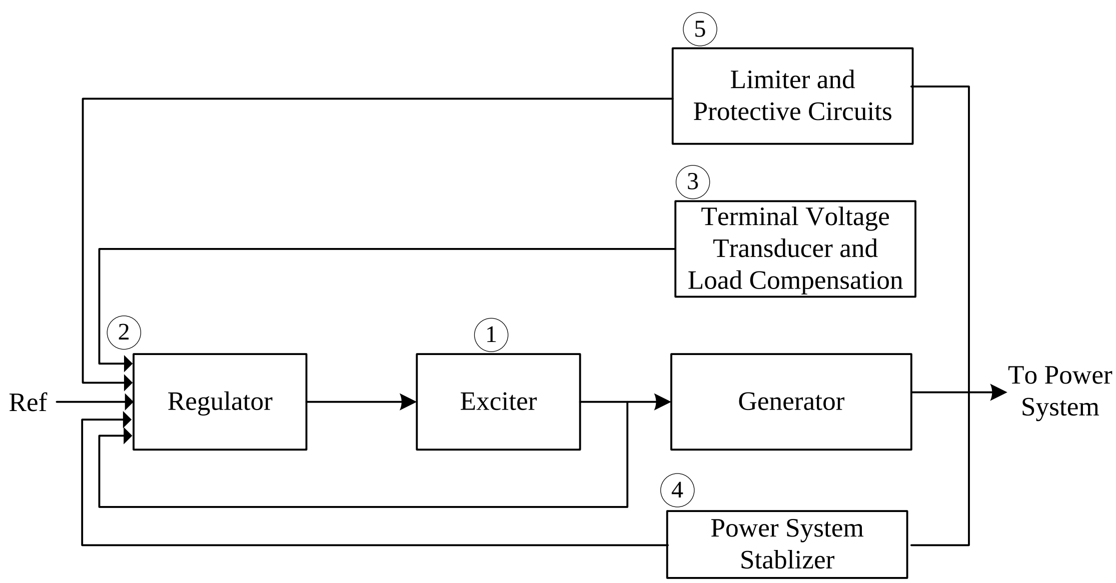

Figure 3-8: Elements of Excitation Systems

- Exciter: Provides dc power to the generator field winding, constituting the power stage of the excitation system.
- Regulator: Processes and amplifies input control signals to a level and form appropriate for control of the exciter. This includes both regulating and excitation system stabilizing

functions (rate feedback or lead-lag compensation).

- Terminal voltage transducer and load compensator: Senses generator terminal voltage rectifies and filters it to dc quantity and compares with a reference which represents the desired terminal voltage. In addition, load (line-drop or reactive) compensation may be provided, if it is desired to hold constant voltage at some point electrically remote from the generator terminal.
- Power system stabilizer*:* provides additional input signal to the regulator to damp power system oscillations. Some commonly used input signals are rotor speed deviation, accelerating power, and frequency deviation.
- Limiters and protective circuits: ensure that the capability limits of exciter and synchronous generator not exceeded. Some of the commonly used functions are the field current limiter, maximum excitation limiter, terminal voltage limiter, volts-per-Hertz regulator and protection, and under excitation limiter.

3.3.3 Control and protective functions of excitation system

Any given system may include only some or all of these functions depending on the specific application and the type of exciter. The philosophy is to have the control functions regulate specific quantities at the desired level, and limiting functions prevent certain quantities from exceeding set limits. If any of the limiters fail, then protective functions remove appropriate components or the unit from service. The following is a brief description of the various control and protective functions of excitation system elements are:

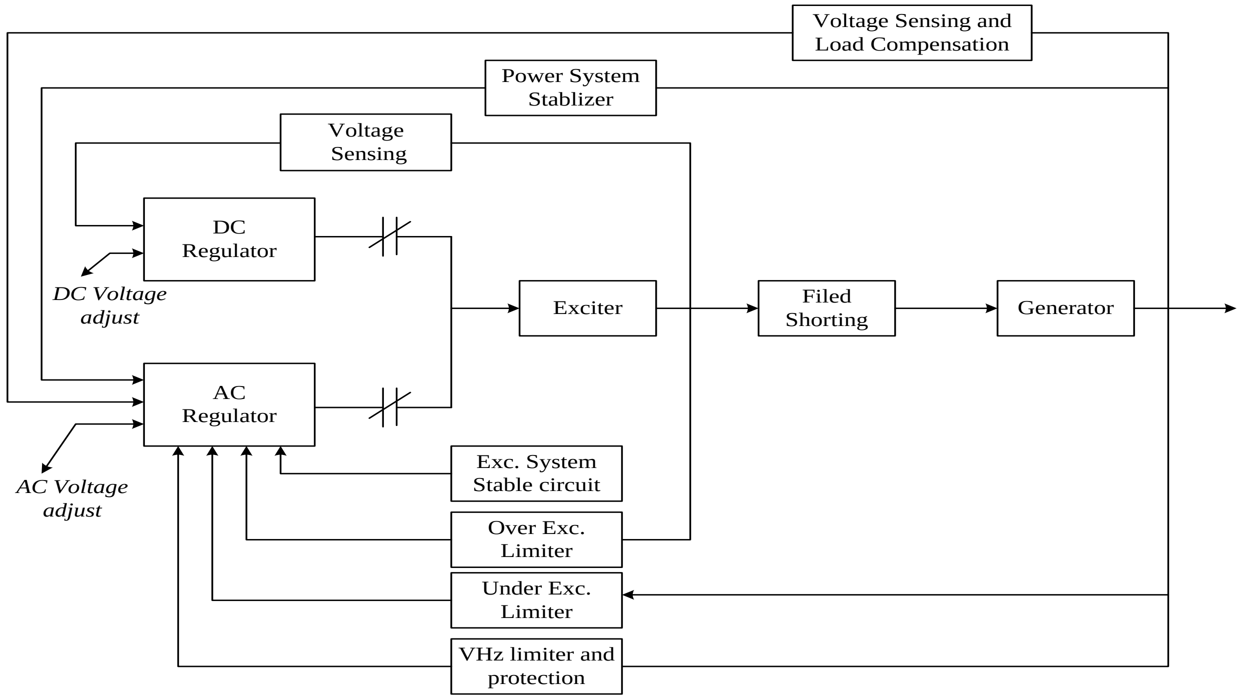

Figure 3-9: Control and protective excitation system

AC voltage regulator: main function is to preserve and maintain generator stator voltage. Its additional function is the generator excitation voltage control.

DC voltage regulator: holds generator excitation voltage on the constant level and is typically manually controlled. Regulator is mainly used during tests, startups and to cover the AC Regulator outages. In this mode of operation the field voltage is regulated.

Excitation systems stabilizing circuits: are used to improve the dynamic performance of the excitation system. As DC and AC excitation systems have elements with significant time constants and it is important to have feedback compensation. The result is minimization of the phase shift caused by elements time constants, what contributes towards generator stable operation such as before the synchronization or after load rejection.

3.3.4 Types of Excitation Systems

Currently there are different types of the excitation systems used worldwide. From the excitation power gain point of view excitation systems could be divided in to the following groups:

Independent: Exciter is not connected to the grid thus excitation parameters do not have direct connection with grid parameters. The part of turbine mechanical power is used for the excitation.

Dependent: Exciter utilizes the part of generator power or is connected to the grid.

Consequently, the excitation source used excitation systems are classified in to three:

1. DC excitation systems
2. AC excitation systems
3. Static excitation systems

DC excitation systems

The excitation of this category utilized direct current generators as sources of excitation power, and provided current to the rotor of the synchronous generator through the slip rings. The exciter may be placed on the same shaft with power generator or is separately driven by a motor. Exciter may be self–excited or with separate excitation, with permanent magnet generator applied.

AC excitation systems

The excitation system of this category utilizes ac machines as sources of the main generator excitation power. Usually, the exciter is on the same shaft as the turbine generator. AC is rectified by controlled or non-controlled rectifiers, to provide DC to the generator field winding. Also AC excitation systems may differ by output control method and source of excitation for the exciter. The following is a description of different forms of ac excitation systems in use.

Stationary rectifier systems: With stationary rectifiers, the dc output is fed to the field winding of the main generator through slip rings. When non-controlled rectifiers are used, the regulator controls the field of the ac exciter, which in turn controls the exciter output voltage. When controlled rectifiers (Thyristor) are used, the regulator directly controls the dc output voltage of the exciter.

Rotating rectifier systems: With rotating rectifiers, the need for slip rings and brushes is eliminated, and the dc output is directly fed to the main generator field; such systems are called brush less excitation systems. It was developed to avoid problems with the use of brushes Perceived to exist when supplying the high field currents of large generators and it does not allow direct measurement of generator field current or voltage.

Static excitation systems

In static excitation systems all the elements are stationary. Such systems directly provide synchronous generator field winding with excitation current by means of slip rings. Rectifiers in static systems gain the power from generator through auxiliary windings or a step-down transformer. In such systems generator itself is power source what means than the generator is self-excited. As the generator is not able to produce any voltage without excitation voltage, the generator must have auxiliary power source to provide field current and energize the generator. Station batteries are usually for the purpose of additional power sources and the process is named field flashing. The following are a description of different forms of static excitation systems in use.

Potential-source controlled rectifier system: In this system, the excitation power is supplied through a transformer from the main generator terminals or the station auxiliary bus, and regulated by a controlled rectifier. This type of excitation system is also commonly known as bus-fed or transformer-fed static excitation system. This system has a very small inherent time constant.

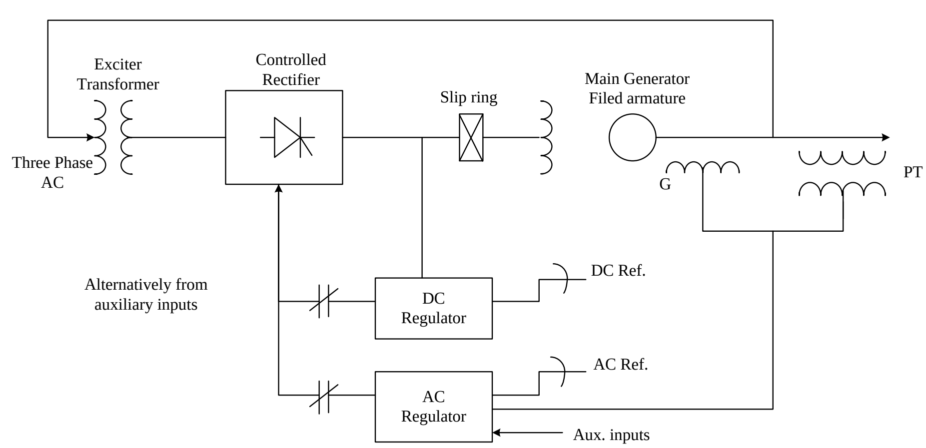

Figure 3-10: Potential source controlled rectifier excitation

Compound-source rectifier system: The power to the excitation system in this case is formed by utilizing current as well as voltage of the main generator. This may be achieved through a power potential transformer (PPT) and a Saturable current transformer (SCT). During a system fault condition, with severely depressed generator voltage, the current input enables the exciter to provide high field forcing capability. Examples of this excitation are the General Electric SCT-PPT and SCPT static excitation systems.

Compound-controlled rectifier system: This system utilizes controlled rectifiers in the exciter output circuits and the compounding of voltage and current derived source within the generator stator to provide excitation power.

The excitation system of Tis Abay II is Static Excitation-Potential-source controlled rectifier system.

3.3.5. Advantages and Disadvantages of Excitation Systems

It must be mentioned that DC systems are less dependent on voltage oscillations, but their control signals have smaller amplification and response time during transients is slow. AC systems benefits in comparison with DC are extended range of excitation current and voltage and higher signals amplification. Brush less exciters advantage is high reliability in using with large generators because of absence the slip rings and brushes. Static exciter merits are response time and sizes of the system. Amplification opportunity and excitation current and voltage are much higher than in DC and AC systems. Sometimes static exciters are even provided with addition field current limiter, because of extremely high ceiling voltage. The main disadvantage of static systems is that power source is main generator and it is self-excited indeed.

The basic function of an excitation system is to provide direct current to the synchronous generator field winding. Excitation controls have functions of both adjusting voltage and damping oscillation by controlling the field voltage.

3.4. Modelling of AVR

AVR is an excitation control that regulates the terminal voltage of the generator based on the terminal voltage feedback. The AVR normally increases the field voltage to quickly recover the terminal voltage to its pre-fault level. Such a fast recovery of the generator terminal voltage will impose a negative effect on the damping of the post-fault oscillation, because the oscillating torque that causes and maintains the oscillation increases relatively with the terminal voltage. The voltage of the generator is proportional to the speed and excitation (flux) of the generator. The speed being constant, the excitation is used to control the voltage. Therefore, the voltage control system is also called as excitation control system or AVR. For the alternators, the excitation is provided by a device (another machine or a static device) called exciter. The block diagram of synchronous generator with automatic voltage regulator is[50]:

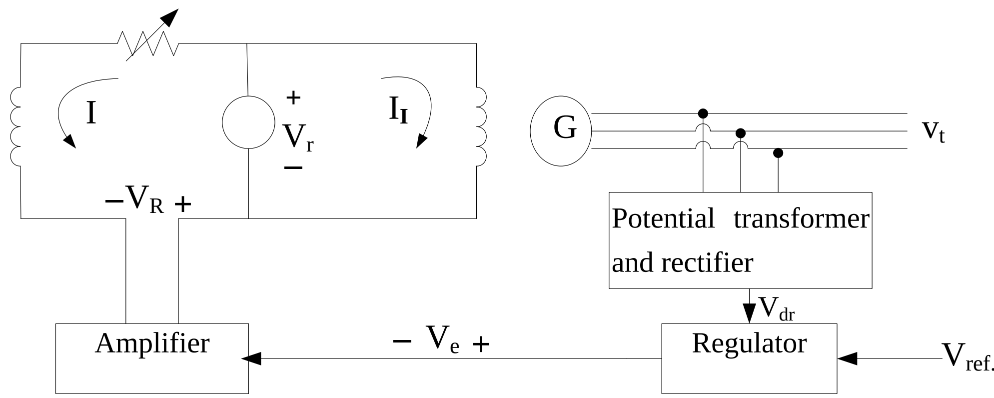

Figure 3-11: Automatic voltage regulator

3.5. Designing of IPFC

Like unified power flow controller (UPFC), the IPFC is a kind of combined compensator's, in which at least two static synchronous series compensator's (SSSCs) are combined via a common DC voltage link. If there is no energy storage system installed in the apparatus, this DC voltage link is usually modelled as a DC capacitor. It is this link that provides the IPFC with the path through which different transmission lines can exchange active and reactive power. In both steady-state analysis and rotor angle stability analysis, the VSC of IPFC can be modelled as a series voltage source injecting an almost sinusoidal voltage with controllable magnitude and angle[41].

Converter

Converters are the most important parts of IPFC system. They play the role of converting AC power to DC power or DC power to AC power. The converter valves are built with GTO power semiconductors. They are provided with R-C snubber and series R-L elements to reduce dv/dt and di/dt stresses that occur during ON/OF transitions.

Converter size

The design of the size of converters in IPFC systems depends basically on the steady performances requirements, i.e. on scheduled active power transport and voltage support requirement. During steady state operation the voltages at the equipment terminals, e.g. converters, shall be within the pre-defined limits. Typical limits are 95% to 105% and 90% to 110%. Strictly speaking, the limits are only applicable to the equipment terminals. However the way power systems are currently designed and operated requires voltage to be kept within limits in the whole power system [42].

Converter Transformers

Transformers are used for converting the system voltage to a value suitable for the converter. For IPFC application standard transformers are used. The leakage reactance of the transformer is usually in the range 0.1-0.2pu [43]. In this thesis work IPFC transmission system development, the converter transformers convert the injected voltage which is suitable for the converters.

DC operating voltage

The large proportion of the cost of IPFC is the cost of the converter bridges. Higher voltage levels, which usually chosen for large power transfer capability [44]. Thus the choice of the voltage levels mainly touches economic issues. As a result, this selection of operating voltages constitutes one-part economic optimization of IPFC transmission installations.

Fundamental frequency component voltage output of the converter can be related to the DC operating voltage by the following equation.

$V_{dc} = V_{do} \cos\alpha$

where: − V_{do} no load voltage

α = delay angle 15^0

$VdC = \frac{3\sqrt{2}}{II} * 13.8V$, Line to line secondary voltage of transformer

= 13.8KV

$$VdC = \frac{3\sqrt{2}}{II} * 13.8KV$$

= 18.637 KV

$$V_{dc} = V_{do} \cos\alpha$$

= 18.637 KV x $\cos 15^0$

= 18KV

DC Capacitor

The dc capacitor is an important part of the converter for maintaining the DC voltage at constant value. Hence, designing the dc capacitor is of a prime importance. The capacitor is designed in a way to achieve a small ripple in the DC voltage. The DC capacitor size is characterized by the time constant defined as a ratio between the DC powers stored at the DC side of the converter to the converter nominal apparent power [45].

In order to obtain a small ripple in the DC voltage, large DC capacitors are required. However, application of large DC capacitors results in slow changes of the DC voltage in response to changes in power exchanged at the DC side of the converter. On the other hand, application of Small DC capacitors results in fast response to changes in instantaneous power exchanged but at the expense of large ripple in the dc voltage. Thus, the total capacitance of the dc capacitors can be approximated by[42]:

$$C_{DC} = \frac{\tau * S_N}{0.5 * V_{DC}^2}$$

Let: τ = 6ms

S_N = 50MW

V_{DC} = 18Kv

$$= \frac{6x10^{-3}x50x10^6}{0.5\ x\ 18KV^2}$$

$$= \frac{300x10^3}{162\ x\ 10^6}$$

= 1.85mf

Placement of IPFC

IPFC provides effective voltage support at the bus to which it is connected to and improves power transfer capability in the transmission line. Hence, in this thesis work, the IPFC is placed at high voltage side of the transformer because of the location of the reactive power support should be as close as possible to the point at which the support is needed because of the change in voltage and consequent power loss in transmission line associated with the reactive power flow and the location of the IPFC at this point is more appropriate and gives a better simulation result.

3.5.1. Mathematical Model of IPFC

Mathematical analysis of IPFC is derived from equivalent circuit. Each IPFC is composed of several VSCs, each of which located in series in the lines with their DC sides connected via a common capacitor. For the purpose of modelling the IPFC, it is considered in the form of several VSCs which have common DC connections. VSC model in the steady state based on FACTS devices is divided into two groups of coupled model and decoupled model. Its coupled model is divided into two main models in turn. The first model is VSM (Voltage source mode). Each converter is formulated as an injections voltage in which control parameters act directly as the state variables. VSM has a good convergence property. The other coupled model is PIM (Power injection model) which is extracted from the VSM. This method keeps the symmetry of admittance matrix[46].

From the equivalent circuit the mathematical analysis is as follows

$for\ V_{sc}$ 1:

$$v_i = L_{s1} * \frac{dI_{ij}}{dt} + R_{s1}I_{ij} + V_{j+}V_{s1} \qquad 3.50$$

$$L_{s1} * \frac{dI_{ij}}{dt} = -R_{s1}I_{ij} + (V_i - V_j) * V_{s1} \qquad 3.51$$

$$\frac{dIij}{dt} = \frac{R_{s1}Iij}{l_{s1}} + \frac{1}{l_{s1}}\frac{(V_{i-}V_j)*V_{s1}}{L_{s1}} \qquad 3.52$$

$for\ V_{sc}$ 2:

$$v_i = L_{s2} * \frac{dI_{ik}}{dt} + R_{s2}I_{ik} + V_{k+}V_{s2} \qquad 3.53$$

$$L_{s2}\frac{dI_{ik}}{dt} = R_{s2}I_{ik} + (V_i - V_k + V_{s2})$$ **3.54**

$$\frac{dI_{ik}}{dt} = \frac{-R_{s2}I_{ik}}{l_{s2}} + \frac{1}{l_{s2}}\frac{(V_i - V_k + V_{s2})}{L_{s2}}$$ **3.55**

In matrix form for VSC1

$$\frac{d}{dt}\begin{pmatrix} I_{ija} \\ I_{ijb} \\ I_{ijc} \end{pmatrix} = \frac{-R_{s1}}{L_{s1}}\begin{pmatrix} I_{ija} \\ I_{ijb} \\ I_{ijc} \end{pmatrix} + \frac{1}{L_{s1}}\begin{pmatrix} V_{ia} & -V_{ja} & -V_{s1a} \\ V_{ib} & -V_{jb} & -V_{s1b} \\ V_{ic} & -V_{jc} & -V_{s1c} \end{pmatrix}$$ **3.56**

In matrix form for VSC2

$$\frac{d}{dt}\begin{pmatrix} I_{ika} \\ I_{ikb} \\ I_{ikc} \end{pmatrix} = \frac{-R_{s2}}{L_{s2}}\begin{pmatrix} I_{ija} \\ I_{ijb} \\ I_{ijc} \end{pmatrix} + \frac{1}{L_{s1}}\begin{pmatrix} V_{ia} & -V_{ka} & -V_{s2a} \\ V_{ib} & -V_{kb} & -V_{s2b} \\ V_{ic} & -V_{kc} & -V_{s2c} \end{pmatrix}$$ **3.57**

To reduce the complexity and to increase the performance of IPFC, mathematical modelling of IPFC is converted to dq0 from ABC component.

$ForV_{sc1}$

$$\frac{d}{dt}\begin{pmatrix} I_{ijd} \\ I_{ijq} \end{pmatrix} = \begin{pmatrix} \frac{-R_{s1}}{L_{s1}} & 1+\omega \\ -(1+\omega) & \frac{-R_{s1}}{L_{s1}} \end{pmatrix}\begin{pmatrix} I_{ijd} \\ I_{ijq} \end{pmatrix} + \frac{1}{L_{s1}}\begin{pmatrix} V_{id} - V_{jd} - V_{s1d} \\ V_{iq} - V_{jq} - V_{s1q} \end{pmatrix}$$ **3.58**

$ForV_{Sc2}$

$$\frac{d}{dt}\begin{pmatrix} I_{ikd} \\ I_{ikq} \end{pmatrix} = \begin{pmatrix} \frac{-R_{s2}}{L_{s2}} & 1+\omega \\ -(1+\omega) & \frac{-R_{s2}}{L_{s2}} \end{pmatrix}\left(\begin{pmatrix} I_{ikd} \\ I_{ikq} \end{pmatrix}\right) + \frac{1}{L_{s2}}\begin{pmatrix} V_{id} - V_{kd} - V_{s2d} \\ V_{iq} - V_{kq} - V_{s2q} \end{pmatrix}$$ **3.59**

Dc link modeling

$$p_{dc} = P_2 - P_1$$ **3.60**

where

$$P_2 = V_{Sd}L_{ik}d - V_{S2}qL_{ik}q$$ **3.61**

$$P_1 = V_{S1} L_{ij} d - V_{S1} q L_{ij} q$$

$$P_{dc} = i_{dc} v_{dc}, i_{dc} = cd\frac{vdc}{dt} \quad \textbf{3.62}$$

$$p_{dc} = v_{dc}\frac{(cdvdc)}{dt} \quad \textbf{3.63}$$

$$\mathrm{c}(vdc\frac{dvdc}{dt}) = (V_{S2d} I_{ikd} + V_{S2q} I_{ikq}) + (\mathrm{V}_{\mathrm{S1d}}\ I_{\mathrm{ijd}} + \mathrm{V}_{\mathrm{S1}q}\ I_{\mathrm{ij}q}).$$

$$\mathrm{c}(\frac{1}{2}\frac{dvdc^2}{dt}) = (V_{S2d} I_{ikd} + V_{S2q} I_{ikq}) + (\mathrm{V}_{\mathrm{S1d}}\ I_{\mathrm{ijd}} + \mathrm{V}_{\mathrm{S1}q}\ I_{\mathrm{ijd}} + \mathrm{V}_{\mathrm{S1}q}\ I_{\mathrm{ij}q}) \quad \textbf{3.64}$$

$$\frac{dvdc^2}{dt} = \frac{2}{c}\left((V_{S2d} I_{ikd} + V_{S2q} I_{ikq} + \mathrm{V}_{\mathrm{S1d}}\ I_{\mathrm{ijd}} + \mathrm{V}_{\mathrm{S1}q}\ I_{\mathrm{ij}q})\right) \quad \textbf{3.65}$$

3.5.2. Control Strategy of IPFC

Control system is an important part of interline power transmission system. This control System maintains Acceptable system voltage through reactive power control. The control tasks insure reactive Power support to the surrounding AC system which increases power reliability and power quality at normal operation and maintains system stability during disturbances. Active power is controlled by controlling phase angles of the converter output voltage or injecting series voltage in series with the transmission line. On the other hand, reactive power is controlled by controlling the magnitude of the output voltage from the converter. The aim of the control of IPFC in transmission line is to improve transient stability of Tis Abay II HEPP.

PI Controller

The control strategy of PI controller is shown in figure 3.9. Here the Vref is compared with corresponding bus voltage Vph – Vph and the error obtained V error is applied to PI control block. Here the limiter output V* is applied to the PWM generator. The PWM generator output is compared with the carrier signal using a comparator, to get desired gate pulses which are used for IPFC [47, 48]. The MATLAB / SIMULINK diagram of conventional PI controller is shown in Fig. 3.12. The PI controlled parameters are KP = 0.6 and Ki = 0.12 seen in Appendix table 3 A 3 governor parameter.

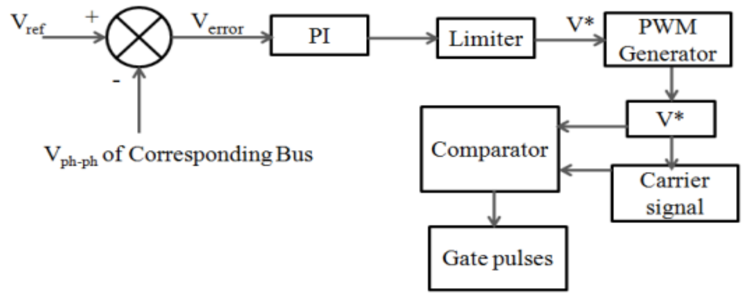

Figure 3-12: Block diagram of PI controller

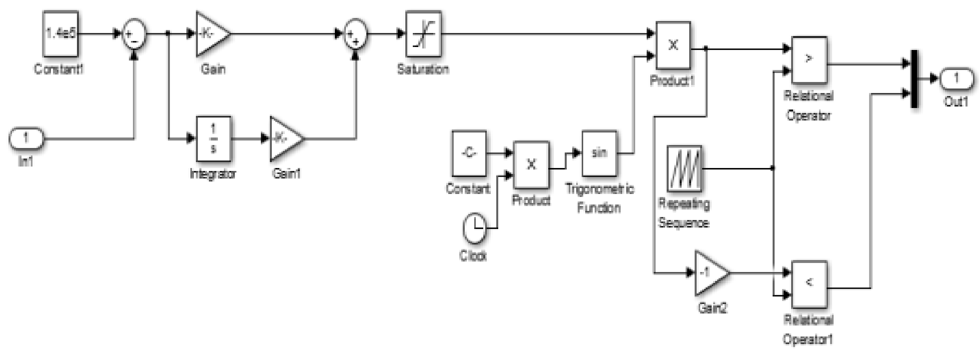

Figure 3-13: Matlab Simulink diagram of PI controller

State Space Equations of IPFC

The state equations of IPFC are non-linear. To simplify the problems, the dc capacitor voltage can be taken as a constant.

The state space equation of IPFC can be determined as follow.

$$\overline{\mathrm{X}} = Ax + Bu$$

$$X = \begin{pmatrix} I_{ijd} \\ I_{ijq} \\ I_{ikq} \end{pmatrix} A = \begin{pmatrix} \frac{-R_{s1}}{L_{s1}} & (1+\omega) & 0 & 0 \\ -(1+\omega) & \frac{-R_{s1}}{L_{s1}} & 0 & 0 \\ 0 & 0 & \frac{-R_{s2}}{L_{s2}} & (1+\omega) \\ 0 & 0 & -(1+\omega) & \frac{-R_{s2}}{L_{s2}} \end{pmatrix} \quad 3.66$$

Control variable

$$U = \begin{pmatrix} \frac{1}{L_{s1}}(\mathrm{V_{id}} - \mathrm{V_{jd}} - \mathrm{V_{s1d}}) \\ \frac{1}{L_{s1}}(\mathrm{V_{iq}} - \mathrm{V_{jq}} - \mathrm{V_{s1q}}) \\ \frac{1}{L_{s2}}(\mathrm{V_{id}} - \mathrm{V_{kd}} - \mathrm{V_{s2d}}) \\ \frac{1}{L_{s2}}(\mathrm{V_{iq}} - \mathrm{V_{kq}} - \mathrm{V_{s2q}}) \end{pmatrix} B = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad 3.67$$

Converter 1 control modelling

$$\frac{d}{dt}\begin{pmatrix} I_{ijd} \\ I_{ijq} \end{pmatrix} = \begin{pmatrix} \frac{-R_{s1}}{L_{s1}} & 0 \\ 0 & \frac{-R_{s2}}{L_{s2}} \end{pmatrix}\begin{pmatrix} I_{ijd} \\ I_{ijq} \end{pmatrix} + \frac{1}{L_{s1}}\begin{pmatrix} V_{id} - V_{jd} - V_{s1d} + (1+\omega)(L_{s1}L_{ijq}) \\ V_{iq} - V_{jq} - V_{s1q} - (1+\omega)(L_{s1}L_{ijd} \end{pmatrix} \quad 3.68$$

$$\overline{X} = AX + BU$$

Where :

$$B = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

$$V_{id} - V_j$$

$$U = \frac{1}{L_{s1}}\begin{pmatrix} V_{id} - V_{jd} - V_{s1d} + (1+\omega)L_{s1}L_{ijq} \\ V_{iq}V_{jq} - V_{s1q} - (1+\omega)L_{s1}L_{ijd} \end{pmatrix} = \begin{pmatrix} U_1 \\ U_2 \end{pmatrix} \quad 3.69$$

$$\frac{d}{dt}\begin{pmatrix} I_{ijd} \\ I_{ijq} \end{pmatrix} = \begin{pmatrix} \frac{-R_{s1}}{L_s} & 0 \\ 0 & \frac{-R_{s1}}{L_{s1}} \end{pmatrix}\begin{pmatrix} I_{ijd} \\ I_{ijq} \end{pmatrix} + \begin{pmatrix} U_1 \\ U_2 \end{pmatrix} \qquad \textbf{3.70}$$

Let control variable can be

$$U_1 = (\mathrm{kp}_{s1} + \frac{K_{is2}}{s})(I*_{\mathrm{ijd}} - I_{\mathrm{ijd}}) + (1+\omega)\,\mathrm{L}_{S1}\, I_{ijq} + V_{id} - V_{jd}$$

$$U_2 = (Kp_{s1} + \frac{K_{is1}}{s})(I*_{ijq} - I_{ijq}) - (1+\omega)\,\mathrm{L}_{S1}\, I_{ijd} + V_{iq} - V_{jd} \qquad \textbf{3.71}$$

Where $I*_{ijd}$ is the Active reference current of Vsc1,

$I*_{ijq}$ is the Reactive reference current of Vsc1

Vsc1 Reference current computation

The power flow equation at bus J

$$\begin{aligned} S_j &= V_j * (I_{ij}^{\ *}) \\ &= (V_{jd} + jV_{jq})(I_{ijd} - jI_{isq}) \\ &= (V_{jd}I_{ijd} + V_{jq}I_{ijq}) + j(-V_{jd}I_{ijq} + V_{jq}I_{ijd}) \\ \therefore P_j &= V_{jd}I_{ijd} + V_{jq}I_{ijq} \end{aligned} \qquad \textbf{3.72}$$

$$Q_j = -v_{jd}I_{jq} + v_{jq}I_{ijd} \qquad \textbf{3.73}$$

$$L_{ijd} = \frac{Q + V_{jd}I_{ijq}}{v_{jq}} \qquad \textbf{3.74}$$

$$P_j = v_{jd}I_{ijd} + v_{jq}I_{ijq} \qquad \textbf{3.75}$$

$$P_j = \frac{v_{jd}(Q + V_{sd}I_{ijq})}{v_{jq}} + v_{jq}I_{ijq} \qquad \textbf{3.76}$$

$$p_j v_{jq} = Q_j v_{jd}(v_{jd}^{\ 2} + v_{jq}^{\ 2})I_{ijq} \qquad \textbf{3.77}$$

$$p_j v_{jq} - Q_j v_{jd} (v_{jd}{}^2 + v_{jq}{}^2) I_{ijq}$$ **3.78**

$$I_{ijq}{}^* = \frac{P_j v_{jq} - Q_j v_{jd}}{v_{jd}{}^2 + v_{jq}{}^2}$$ **3.79**

Reactive component

$$I_{ijd} = \frac{P_j v_{jq} - Q_j v_{jd}}{v_{jq}}$$ **3.80**

$$I_{ijq} = Q + \frac{\dfrac{(P_j v_{jq} - Q_j v_{jd})}{v_{jd}{}^2 + v_{jq}{}^2}}{v_{jq}}$$ **3.81**

$$I_{ijd} = \frac{Q_j (\mathrm{v_{jd}}{}^2 + v_{jq}{}^2) + p_j v_{jd} v_{jq} - Q_j v_{jd}{}^2}{v_{iq} (v_{jd}{}^2 + v_{jq}{}^2)}$$ **3.82**

$$= \frac{Q_j\ \mathrm{v_{jd}}{}^2 + Q_j v_{jp}{}^2 - Q_j v_{jd}{}^2 + p_j v_{jd} v_{jq}}{v_{jq} (v_{jd}{}^2 + v_{jq}{}^2)}$$ **3.83**

$$= \frac{Q_j\ \mathrm{v_{jq}}{}^2 + p_j v_{jd} v_{jq}}{v_{jq} (v_{jd}{}^2 + v_{jq}{}^2)}$$ **3.84**

$$\therefore I_{ijd}{}^* = \frac{Q_j v_{jq} + P_j v_{jd}}{v_{jd}{}^2 + v_{jq}{}^2}$$ **3.85**

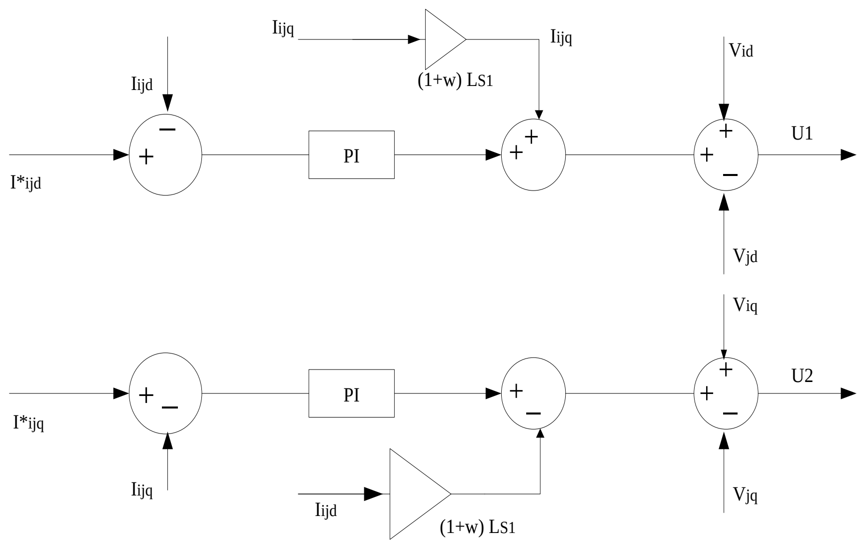

Figure 3-14: Block diagram of master converter (VSC1) IPFC controller

Voltage source converter 2 (Slave converter) modelling

$$\frac{d}{dt}\begin{pmatrix} I_{ikd} \\ I_{ikq} \end{pmatrix} = \begin{pmatrix} \frac{-R_{s2}}{L_{s2}} & 0 \\ 0 & \frac{-R_{s2}}{L_{s2}} \end{pmatrix}\begin{pmatrix} I_{ikd} \\ I_{ikq} \end{pmatrix} + \frac{1}{L_{s2}}\begin{pmatrix} V_{id} - V_{kd} - V_{s2d} + (1+\omega)L_{s2}I_{ikq} \\ V_{iq} - V_{kq} - V_{s2q} - (1+\omega)L_{s2}I_{ikd} \end{pmatrix}$$ **3.86**

$$\bar{X} = Ax + BU......B = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$ **3.87**

$$U = \frac{1}{L_{s2}}\begin{pmatrix} V_{id} - V_{kd} - V_{s2d} + (1+\omega)I_{ikq}L_{s2} \\ V_{iq} - V_{kq} - V_{s2q} - (1+\omega)I_{jkd}L_{s2} \end{pmatrix}$$ **3.88**

$$\frac{d}{dt}\begin{pmatrix} I_{ikd} \\ I_{ikq} \end{pmatrix} = \begin{pmatrix} \frac{-R_{s2}}{L_{s2}} & 0 \\ 0 & \frac{-R_{s2}}{L_{s2}} \end{pmatrix}\begin{pmatrix} I_{ikd} \\ I_{ikq} \end{pmatrix} + \begin{pmatrix} U_1 \\ U_2 \end{pmatrix}$$ **3.89**

Let control variables

$$U_1 = (\mathrm{kp}_{s1} + \frac{K_{is2}}{s})(I*_{\mathrm{ijd}} - I_{\mathrm{ijd}}) + (1+\omega)\,\mathrm{L}_{S1}\, I_{ijq} + V_{id} - V_{jd}$$

$$U_2 = (Kp_{s1} + \frac{K_{is1}}{s})(I*_{ijq} - I_{ijq}) - (1+\omega)\,\mathrm{L}_{S1}\, I_{ijd} + V_{iq} - V_{jd}$$

3.90

V_{SC2} (slave converter) reference current computation.

The direct axis component of VSC2 is depending on only the DC-voltage (storage capacitor).

$$\mathrm{I}*_{ikd} = (\mathrm{kp}_{s2} + \frac{K_{is2}}{s})(V*_{\mathrm{dc}} - V_{\mathrm{dc}})$$ **3.91**

And the quadrature component of slave converter (V_{SC2}) is obtained as follows. It is depending on the real power flow through converter two (V_{SC2}).

$$I*_{ikq} = (\mathrm{kp}_{s2} + \frac{K_{is2}}{s})(V*_{i} - V_{\mathrm{i}})$$

3.92

Therefore the block diagram of slave converter controller is shown in fig 3.15.

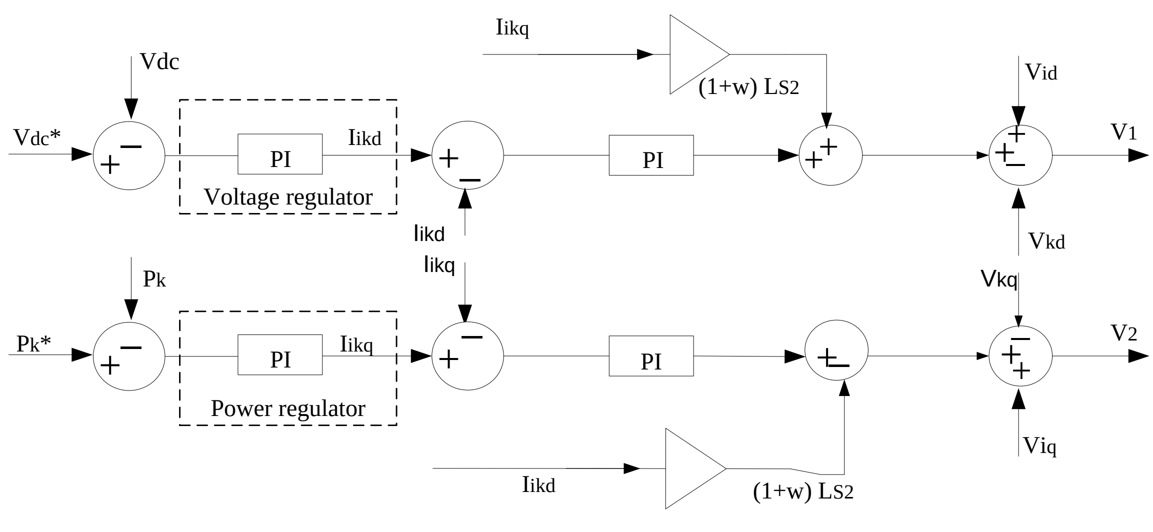

Figure 3-15: Block diagram of slave converter (VSC2) IPFC controller

CHAPTER FOUR

4. SIMULATION RESULTS AND DISCUSSION

In this thesis the effect of IPFC in Tis Abay power generation system is analyzed and various parameters such as voltage profile, Active power, reactive power, load angle and stator current improvement was investigated. Objectives are achievable by control settings of the IPFC controllers. Simulation results show the effectiveness of IPFC to control the real and reactive powers as well as voltage magnitude and current magnitude. It is found that there is an improvement in the real power and reactive power and voltage & current magnitude through the transmission line when IPFC is connected. Tis Abay hydro power generation system modelings have been done.

Finally this thesis focus on the generation station running at steady state and when fault happened in generation system to compare and see the performance of IPFC to enhance transient stability of the system.

The modeling and analysis of synchronous generator, HTG and excitation system controller have been done using MATLAB/SIMULINK software. Also the design and modeling of IPFC is developed and the simulation results of the system with and without IPFC are carried out due to the occurrence of fault like three phase to ground and line to line fault.

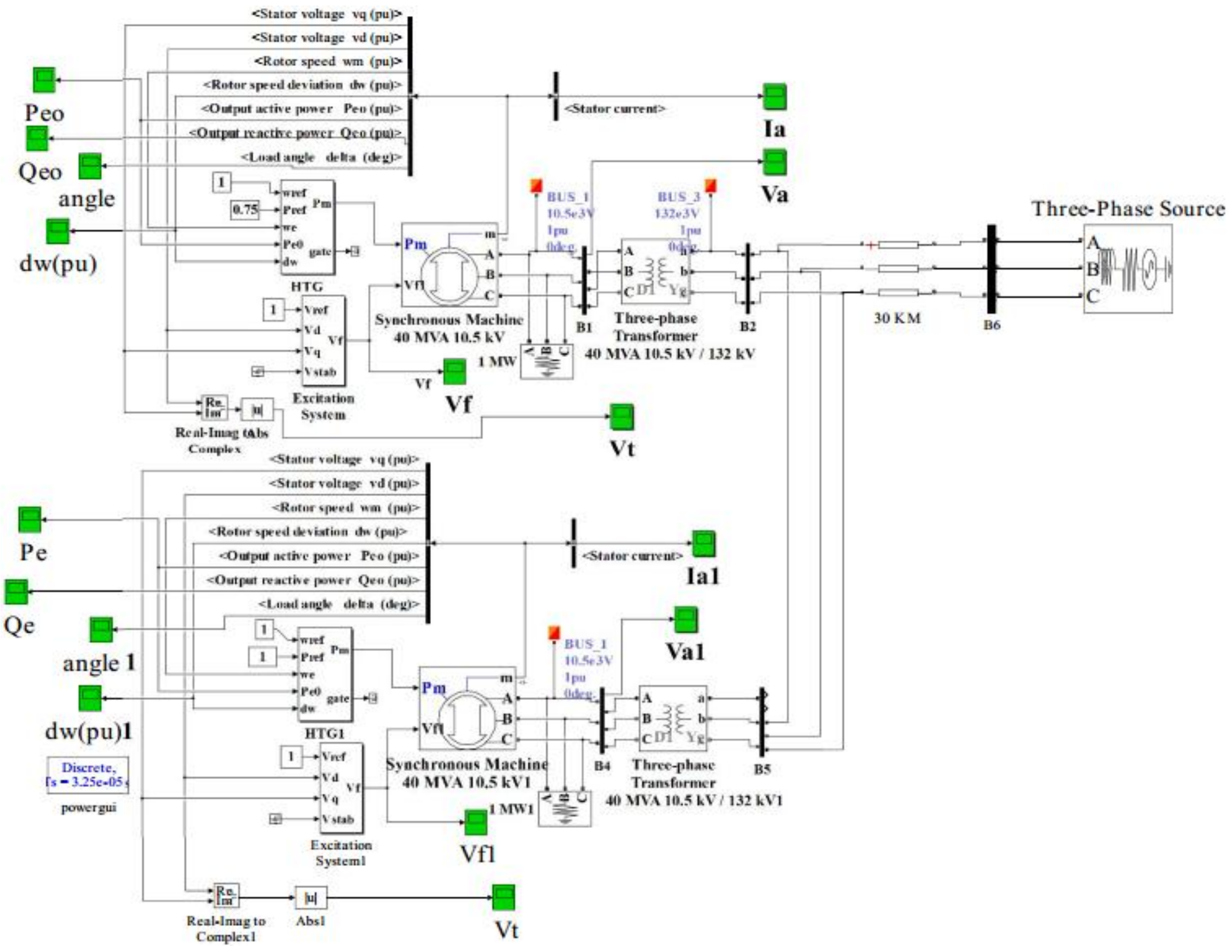

Figure 4-1: Model of Tis Abay II Hydro Power Generation System

4.1 Systems Running at Steady State Condition

The Simulink model illustrates the use of the synchronous machine associated with the hydraulic turbine and governor (HTG) and excitation system blocks.

Figure 4.1 shows the Simulink models of the system under steady state condition. Double line having the same properties are used and fed by two generators& transformers in this case. The objective of the transient stability study is to ascertain whether the load angle returns to a steady value following the clearance of the disturbance. However, in this thesis paper simulation results have been done for the parameters like active power, reactive power, load angle, excitation voltage, stator current, rotor speed, terminal voltage, and line voltage of the generator to show clearly the transient stability of power system enhancement.

Active power of Tis Abay II Power Generation at steady state

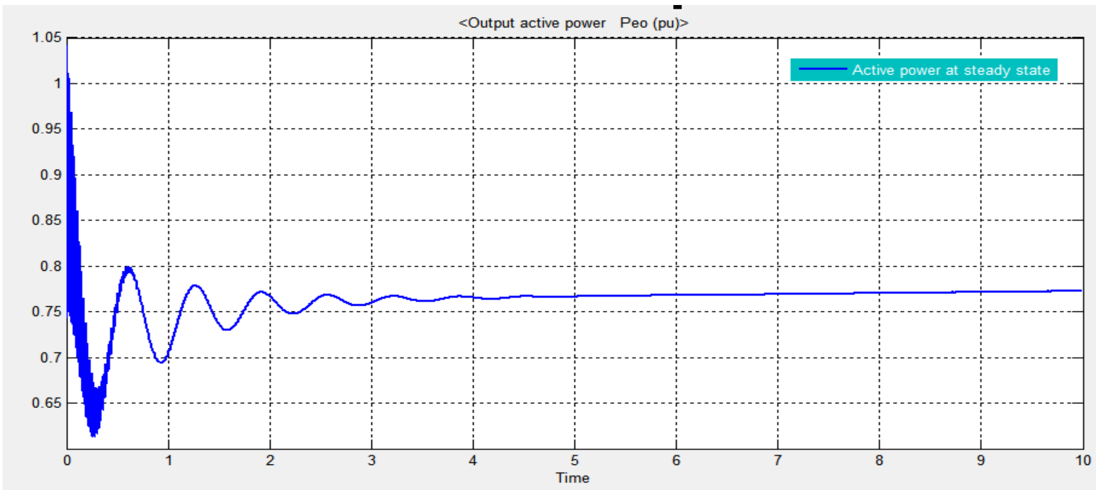

Figure 4-2: Simulation result of active power at steady state.

Reactive power of Tis Abay II hydroelectric power generation at steady state

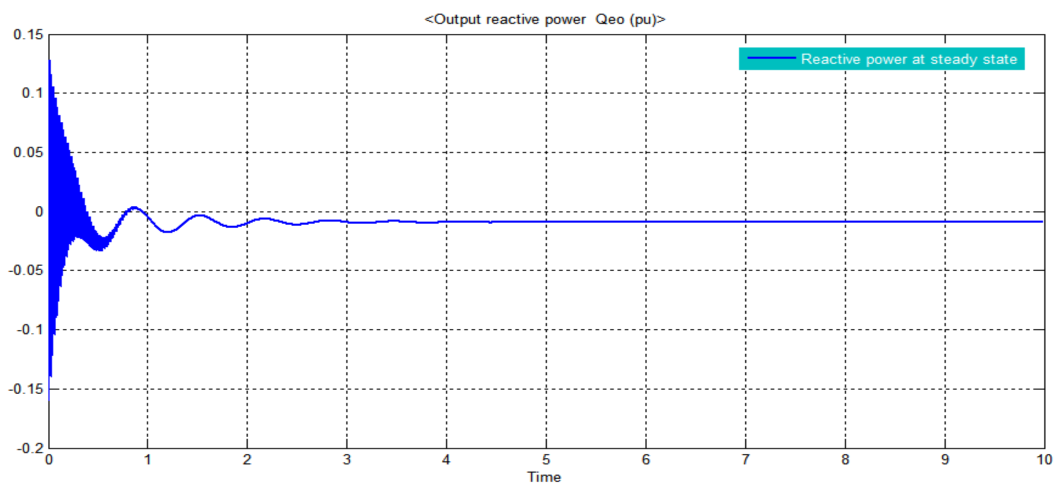

Figure 4-3: Simulation result of reactive power at steady state condition.

Fig 4.2 and 4.3 shows the Matlab Simulink simulation result of active and reactive power of synchronous generator at steady state condition. During normal conditions, the mechanical torque input to the turbine applied to the generator rotor shaft produces electric power output from the generator. In steady state, the rotor therefore runs at a constant speed with this balance of electric and mechanical torque.

Load angle of Tis Abay II hydroelectric power system at steady state

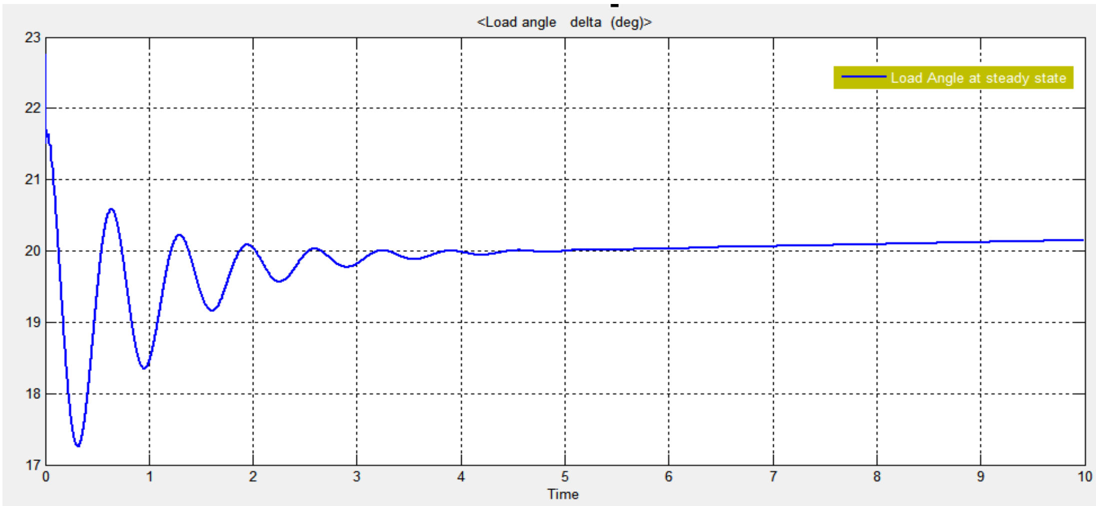

Figure 4-4: Simulation result of load angle at steady state condition

From the definition load angle stability refers to the ability of synchronous machines of an interconnected power system to remain in synchronism after being subjected to a disturbance. The graph shows the load angle is increased at 22.9^0 finally, after t=3.5 second it oscillates at 20 degree.

Excitation voltage of Tis Abay II hydroelectric power system steady state

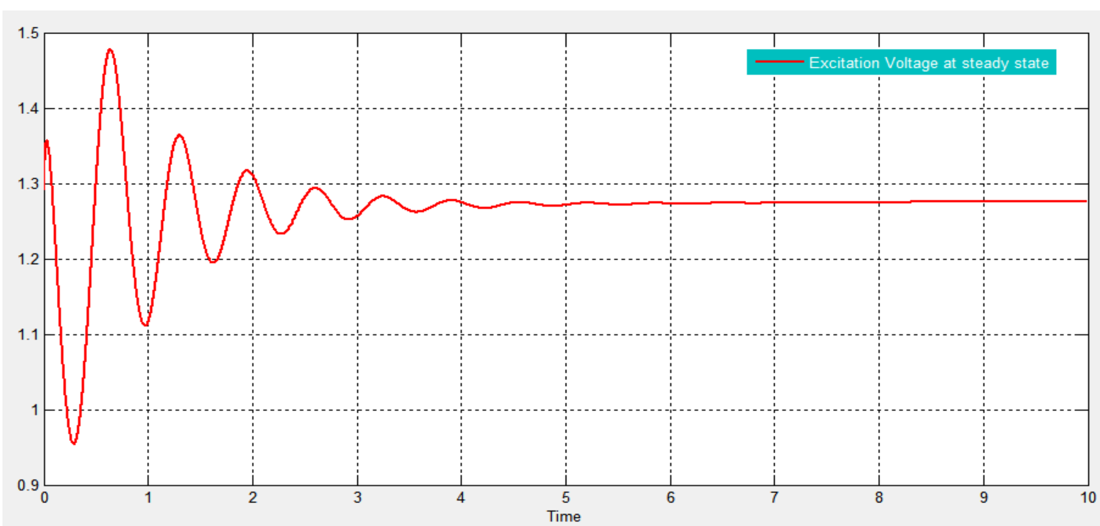

Figure 4-5: Simulation result of Excitation voltage at steady state condition

At the beginning of the simulation result in figure 4.5, the excitation voltage starts at 1.3 p.u and increasing till it reaches nearly 1.5 p.u. Finally, after t= 5second, during full load operation it falls 1.29 p.u.

Stator current of Tis Abay II hydroelectric power system at steady state

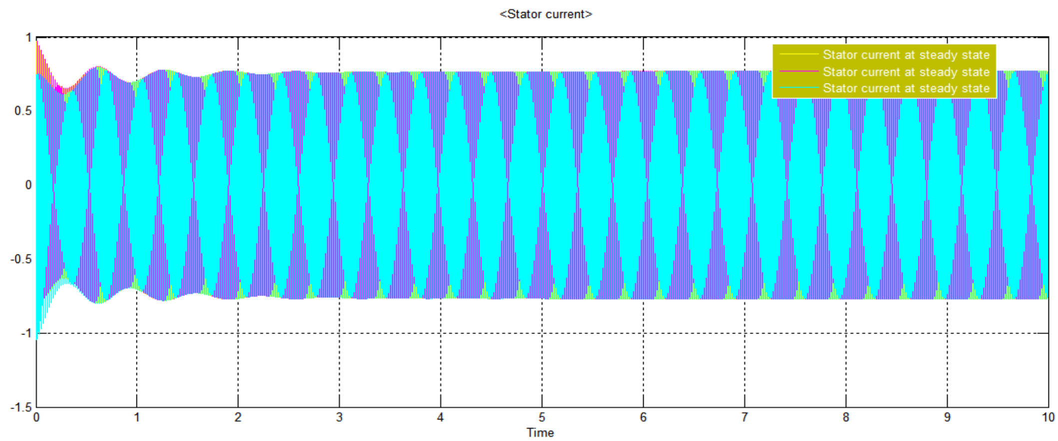

Figure 4-6: Output result of stator current at steady state condition

Rotor speed of Tis Abay II hydroelectric power system at steady state

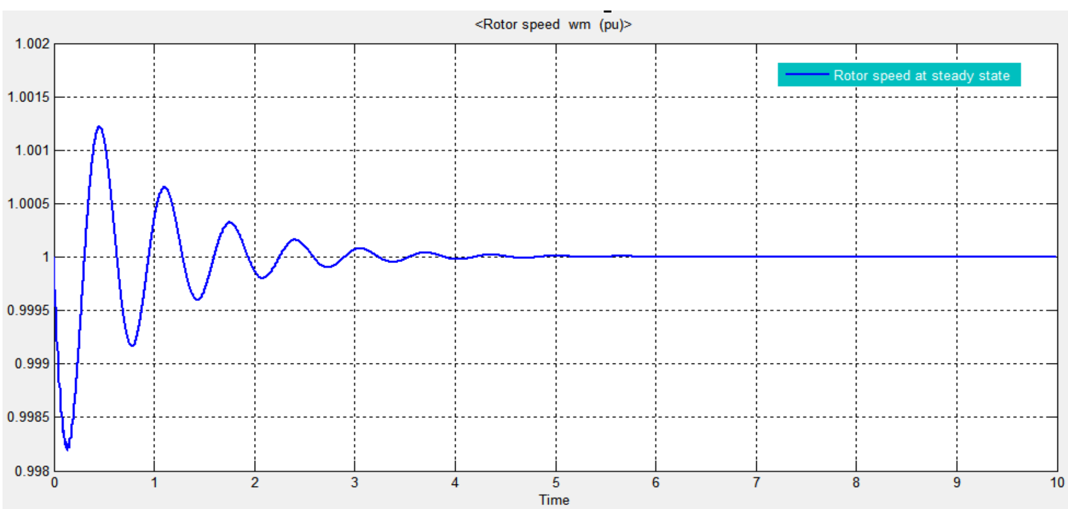

Figure 4-7: Output result of rotor speed at steady state condition.

For a synchronous generator, the magnetic field rotates at synchronous speed and the rotating magnetic field is created in the stator. But rotor speed is the actual generator speed. So from the simulation result shown in figure 4.7 the rotor speed deviation starts from 0 and oscillates below-1.8×10^{-3} p.u.

Terminal voltage of Tis Abay power generation steady state.

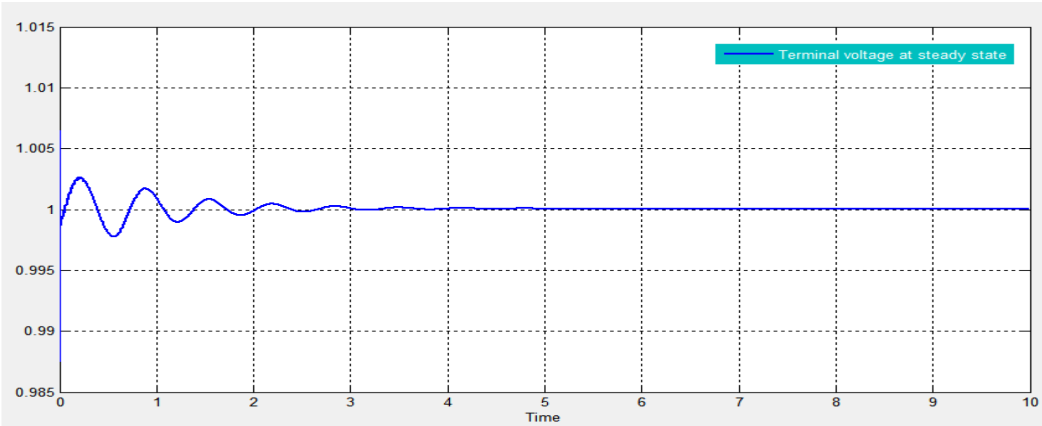

Figure 4-8: Output result of terminal voltage at steady state condition

Voltage stability refers to the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition. The additional of power system stabilizer is to damp the oscillation of power system and the automatic generation control is to maintain the system frequency at nominal value. But we observed from the simulation result, they are a very small significant affected the terminal voltage of the system because the terminal voltage of the synchronous generator is controlled by automatic voltage regulator.

At normal operation the model runs in steady state. Figure 4.8 Shows that the terminal voltage Vt is 1.0 p.u. throughout the simulation.

Line voltage of Tis Abay II Hydro Power Generation at steady state.

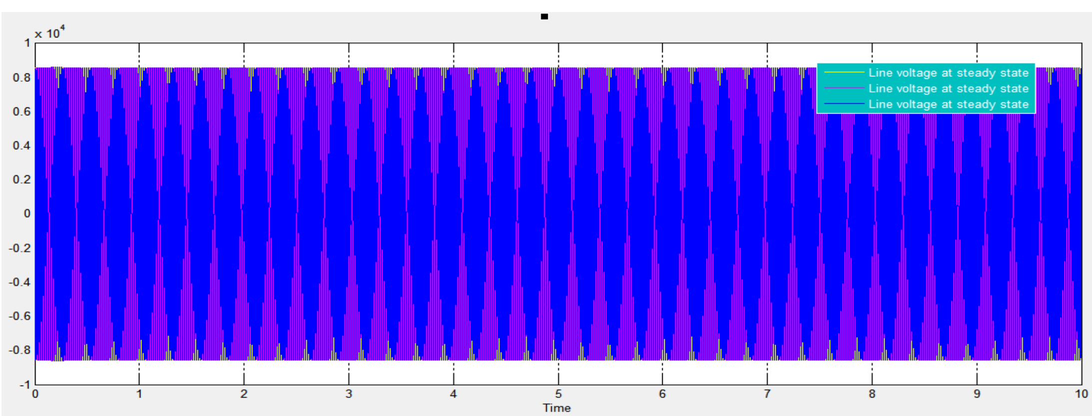

Figure 4-9: Simulation result of line voltage at steady state condition

The simulation result in figure 4.9 shows line voltage oscillate at steady state without any distortion at 0.9 p.u. through ought out simulation. Under normal condition acceptable voltage is expected. Otherwise disturbance will happen.

4.2 System running at fault condition

4.2.1 Simulation result of the system three phase fault with and without IPFC

Simulation is performed a three phase to ground fault on the transmission line. This fault which is initiated at t= 0.8 sec and is cleared at 1 sec. From the block diagram seen in figure 4.10 Double lines having the same properties are used and fed by two generators and transformers in this case. Assuming that a synchronous machine is connected to an infinite bus, The fault occurred at transmission line and using IPFC are as shown in figure 4.10 and 4.11 below.

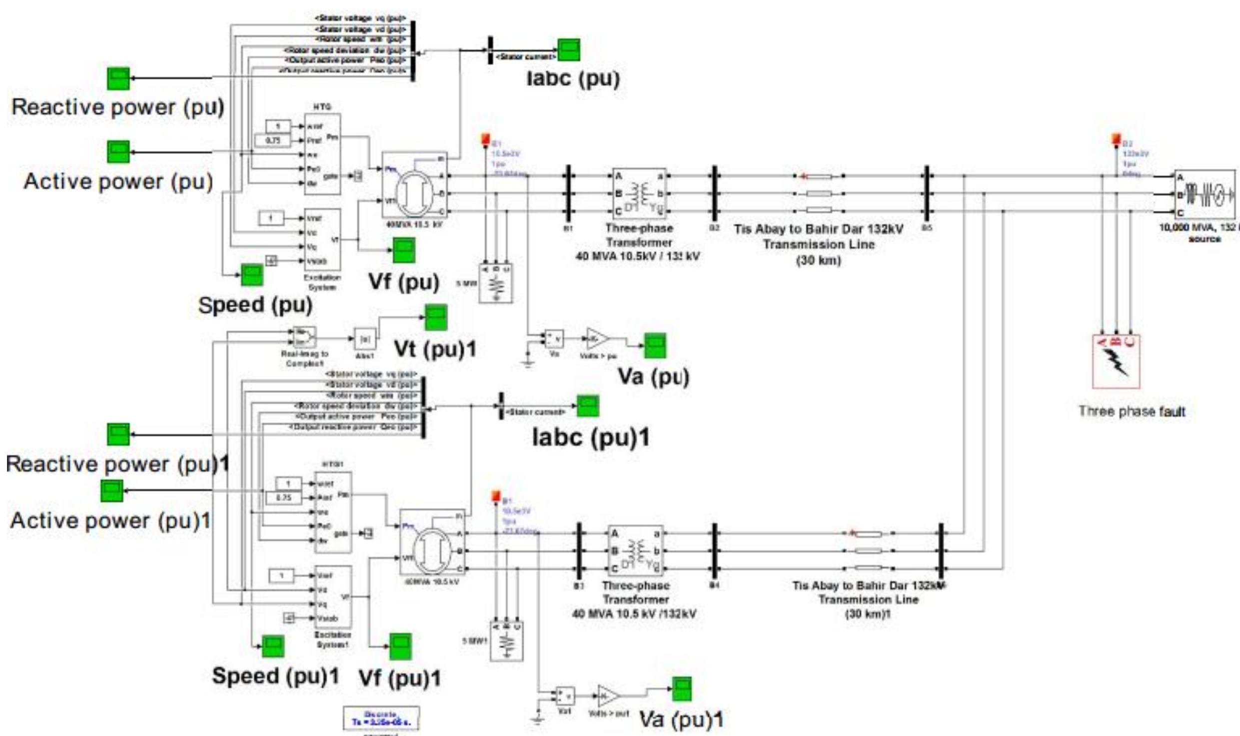

Figure 4-10: Model of Tis Abay Power Generation System with 3 phase to ground fault

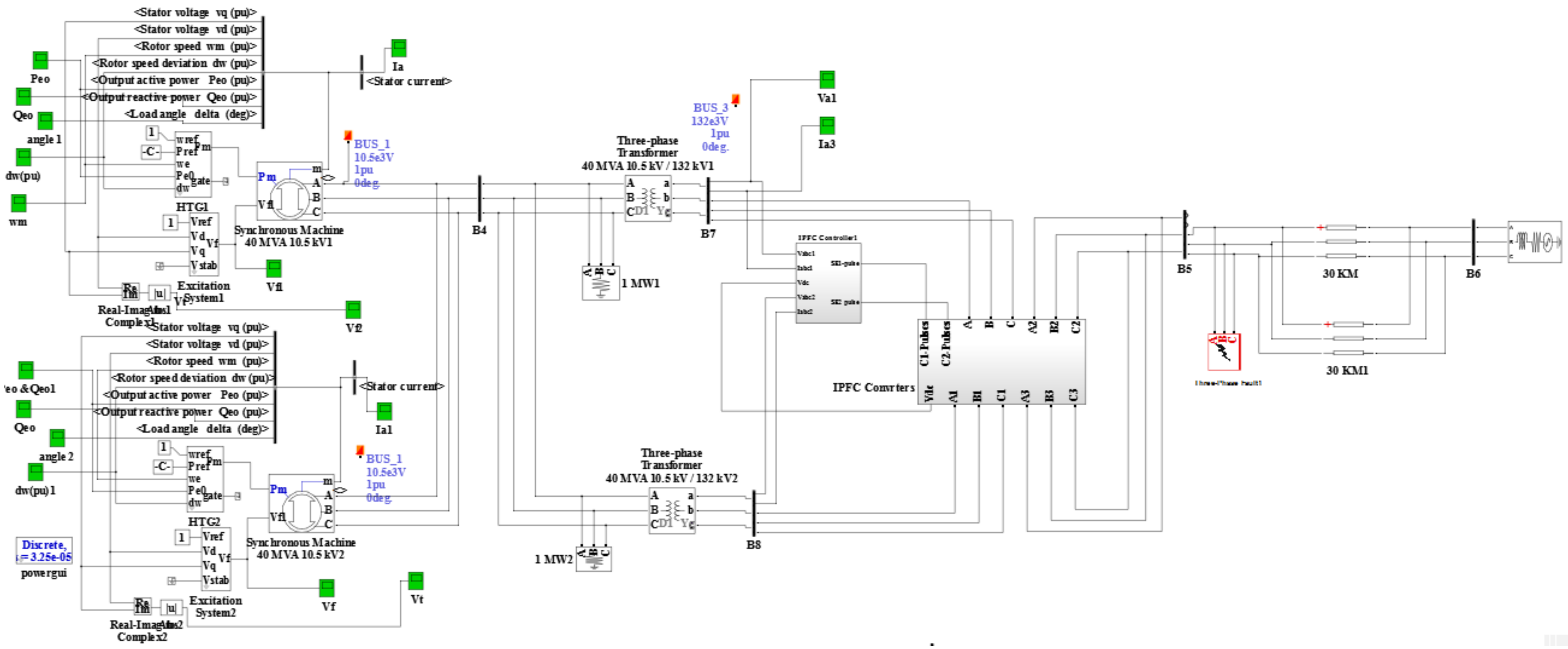

Figure 4-11: Model of Tis Abay Generation System 3 phase to ground fault with IPFC

Active power of Tis Abay hydro power generation at fault condition

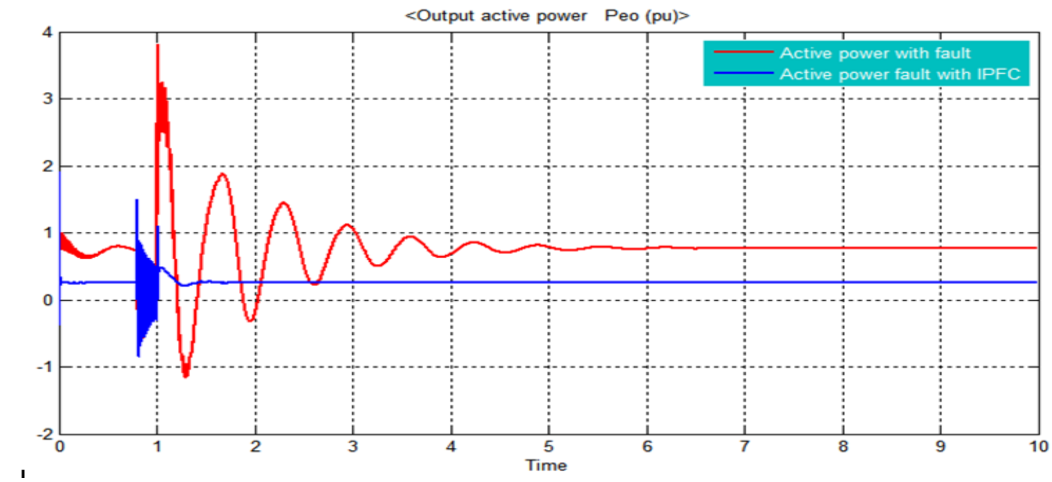

Figure 4-12: Simulation result of Active power with 3 phase to ground fault

From the simulation result in figure 4.12 shows that when the power system is connected with interline power flow controller the stability of the system is quickly at 1.5 seconds compared to that of without IPFC. So when the settling time is reduced the magnitude of the oscillation is decreased and the stability of the system is increased. This meant Interline power flow controller achieved the settling time by 79 % quicker than conventional controller

Reactive power output drops suddenly when the frequencies rise. From the simulation result the system with conventional power system while subjected to a disturbance is achieved the desired value of output reactive power after 5 seconds.

Reactive power of Tis Abay hydro power generation at fault condition

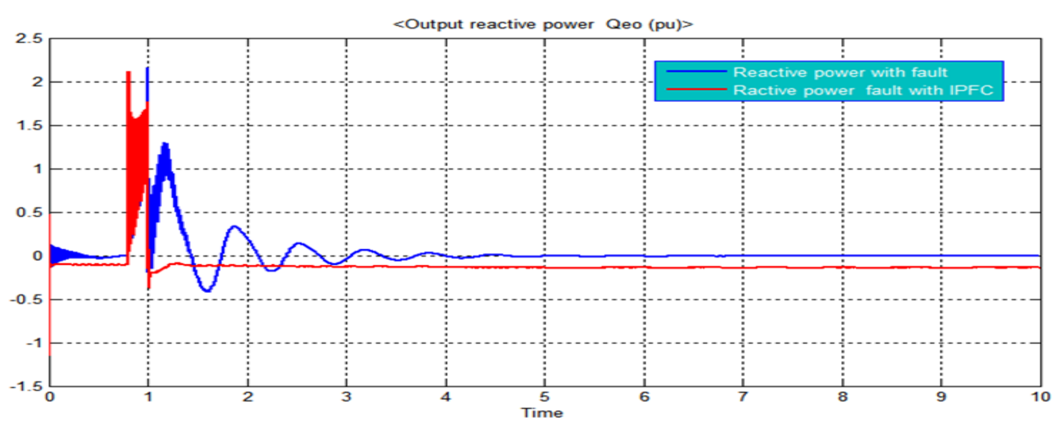

Figure 4-13: Simulation result of reactive power 3 phase to ground fault

From the Matlab/Simulink simulation result, figure 4.13, shows that the system operated with Interline power flow controller achieved that the reactive power is quickly reached to nominal value. The oscillation rise around 2.3 p.u during the fault happened in both cases. But it takes 1 second stable time using IPFC. Therefore IPFC improves the reactive power by 80%.

Load angle of Tis Abay power generation system with three phases to ground fault

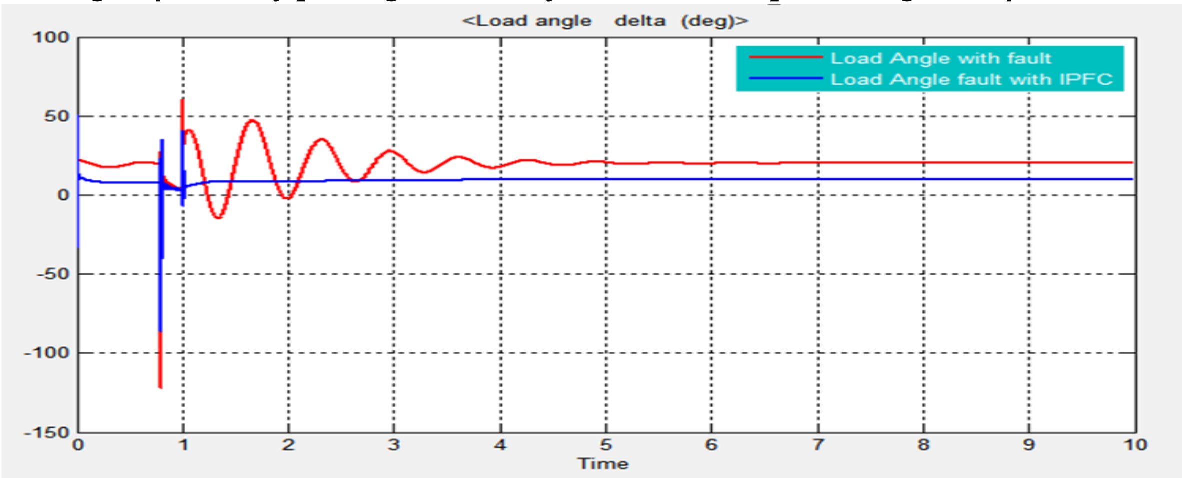

Figure 4-14: Output result of Load angle with 3 phase to ground fault

The load angle in figure 4.14 shows the rotor angle of each machine during the three phase fault. The generator speed decreases and the real power output the generator reduced and reactive power output increases. The IPFC balance the active power and reactive power in the line so as to keep the load angle within the limit. The load Angle output of the generator at fault condition without IPFC oscillates between -145^0 and 60^0. The oscillation stability time starts at 4.5 sec.

Load angle stability refers to the ability of synchronous machines of an interconnected power system to remain in synchronism after being subjected to a disturbance. It depends on the ability to maintain/restore equilibrium between electromagnetic torque and mechanical torque of each synchronous machine in the system. By comparing both graph in Fig.4.16 I observed that the system operated with interline power flow controller the load angle output of the generator at fault condition with IPFC is maintained the oscillation between -59^0 and 40^0 compared to without IPFC and the oscillation is stable quickly after 1.2 sec. This means that IPFC achieved the settling time by 70% quicker than conventional controller.

Excitation voltage of Tis Abay hydropower generation at fault condition

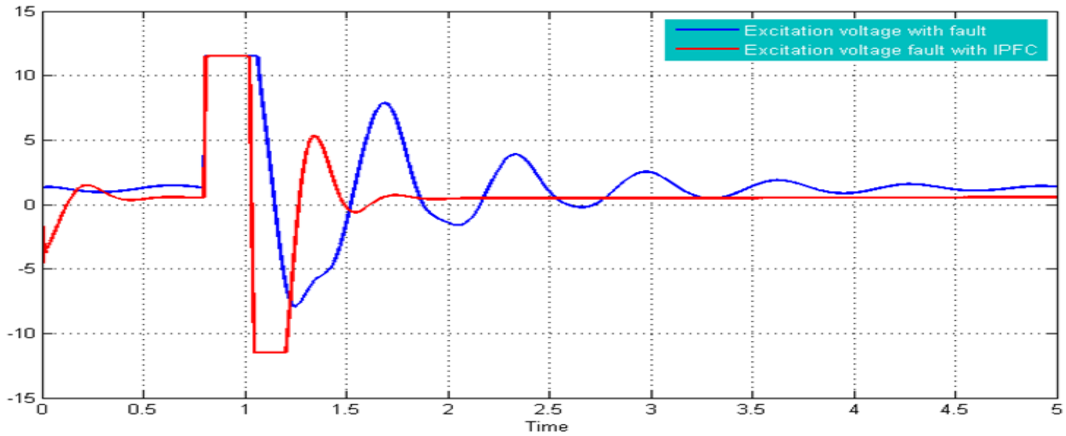

Figure 4-15: Simulation result of Excitation voltage with 3 phase to ground fault

From the simulation result it is observed that the excitation voltage can go as high as around 11 p.u which it does during the fault in both cases. It will return to steady state after 5 seconds when fault is cleared without IPFC. But when IPFC is connected it stables quickly after 1.5 sec. Since the oscillation is settled quickly IPFC achieved the settling time by 70%.

Stator current of Tis Abay hydropower generation at fault condition

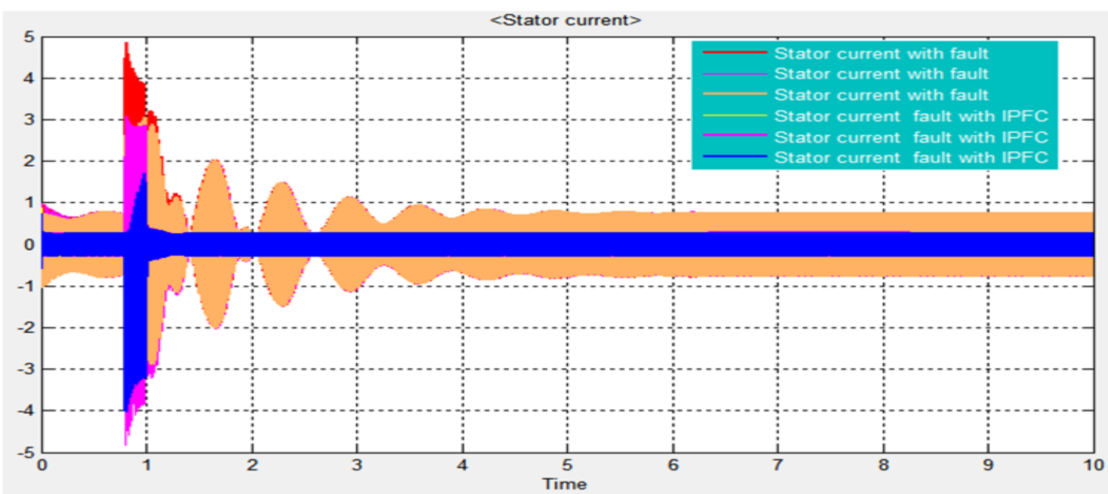

Figure 4-16: Simulation result of Stator current 3 phase to ground fault

From the simulation result the stator current increases significantly at the time of fault and reaches about 5 p.u during the transient state to steady state. When IPFC is connected with the system the stator current oscillates between 4 p.u and -4 p.u. During the period of fault, the oscillation stable quickly with IPFC after 1 second. So comparing in both cases more time is taking to stable without IPFC, i.e. after 4.5 seconds. But the time taking to be stable with IPFC is 1.2 seconds. So IPFC achieved the settling time by 70 %.

Rotor speed of Tis Abay hydropower generation at fault condition.

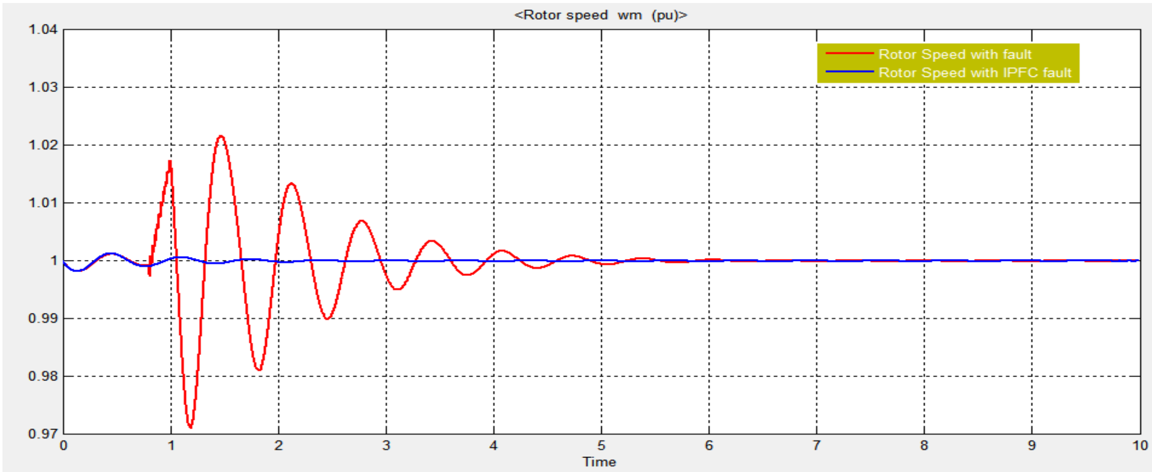

Figure 4-17: Output result of rotor speed with 3 phase to ground fault

From the simulation result in figure 4.17 the oscillation of the rotor speed of the synchronous generator was un damped for the simulation time set after 10 seconds. The amplitude increases to about 1.01 p.u during fault, then decreases 0.90 p.u and oscillate around nominal value (1.0 p.u) as the governor system regulates it. The speed takes much longer than the terminal voltage to stabilize, mainly because the rate of valve opening /closing in the governor system is limited to 0.1 p.u/s.

From the simulation result shown in figure 4.417, we observed the mechanical rotor speed (pu) of the system with three phase to ground fault. First by comparing both graph the time taken to damp the oscillation is 7 seconds and 2.0 seconds respectively and oscillates around nominal value (1.0 pu) after the fault is cleared. The rotor speed with IPFC controller will achieve the settling time by 64% quicker than conventional controller.

Terminal voltage of Tis Abay hydro power generation at three phase fault condition

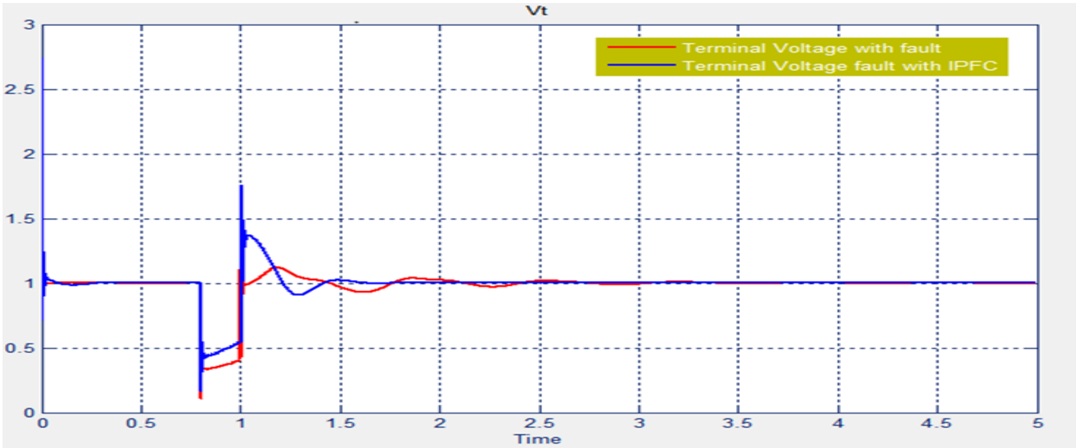

Figure 4-18: Simulation result of terminal voltage with 3 phase to ground fault.

From the simulation result shown in figure 4.18, the voltage drops during the period of fault falls to about 0.1p.u. So this might bring the system to trip and shut down. Hence, without IPFC the terminal voltage takes a long time to come back (recover) after the fault is cleared compared to with IPFC. This recognizes the need for some compensating device in Tis Abay hydroelectric power generation system.

With addition of an IPFC at the transmission line, the voltage drop initiates the operation of the IPFC. The drop in the terminal voltage determines the amount of reactive power needed and the IPFC can operate at full capacity even at low voltage levels. In this case, the voltage drop significantly improved to a value around 0.5 p.u during the fault and the voltage is immediately restored to 1.5sec with IPFC as shown in figure 4.24. This is much improved performance as compared to the case without IPFC and the voltage restored is 3.5sec. So IPFC improves the settling time by 65%.

Line voltage of Tis Abay hydro power generation system at fault condition.

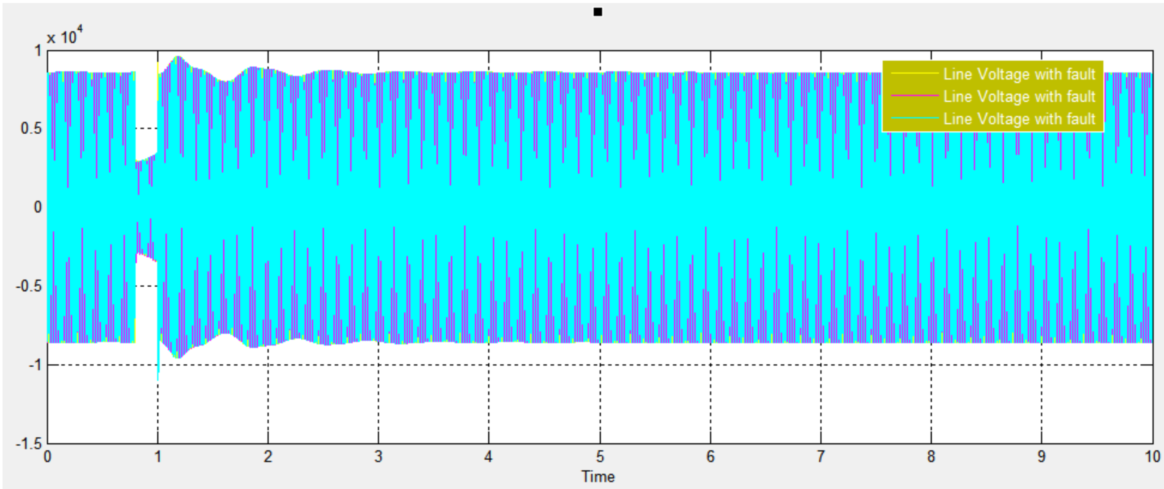

Figure 4-19: Simulation result of Line voltage with 3 phase to ground fault.

From the simulation result shown in figure 4.19 it is observed that the line voltage is almost 1.0 p.u at the beginning of the simulation. It falls to about 0.4 p.u during the fault and returns to nominal quickly after the fault is cleared.

Line voltage of Tis Abay hydropower generation system at fault condition with IPFC.

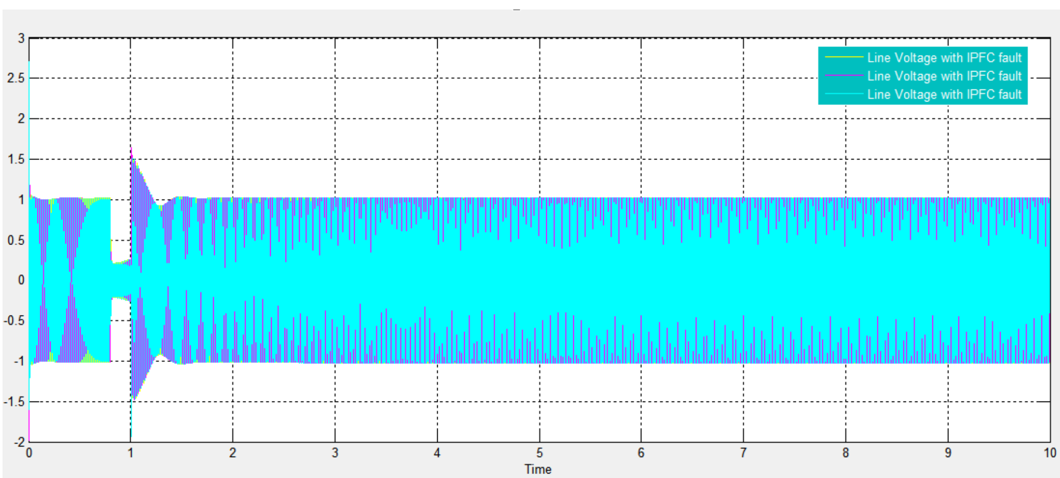

Figure 4-20: Simulation result of line voltage 3 phase to ground fault with IPFC

From the simulation result shown in figure 4.20 the voltage output of the generator oscillates between around 0.3 p.u and -0.3 p.u as shown in figure during the period of fault. The oscillation is stable quickly with IPFC.

4.2.2 Simulation Result with Line to Line fault

Active power of Tis Abay power generation system phase to phase fault

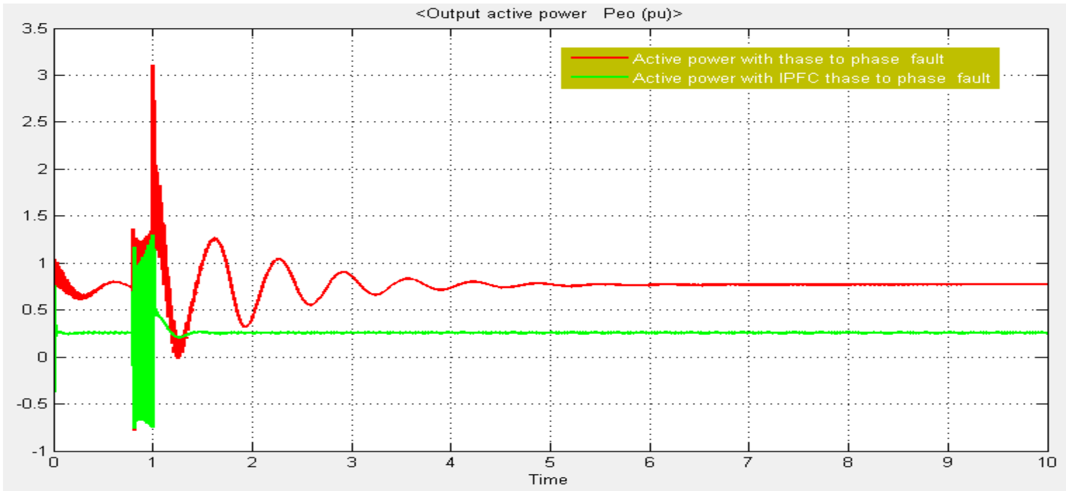

Figure 4-21: Matlab simulation result of active power phase to phase fault

From the simulation result, it is observed that the system is achieved the value 3.0 p.u of output active power when line to line fault occurred without IPFC connection and it takes much time to become steady state after the fault is cleared.

From the simulation result, by comparing both graph Fig.4.21 it is observed that the system operated with interline power flow controller achieved the desired value 1.5 p.u of output active power compared to conventional controller. The system with conventional controller while subjected to disturbance will achieve the desired value of output active power (p.u) at 6 seconds while system with IPFC achieve the desired value at 1.5 seconds and also decrease the oscillations.

Reactive power of Tis Abay power generation system phase to phase fault

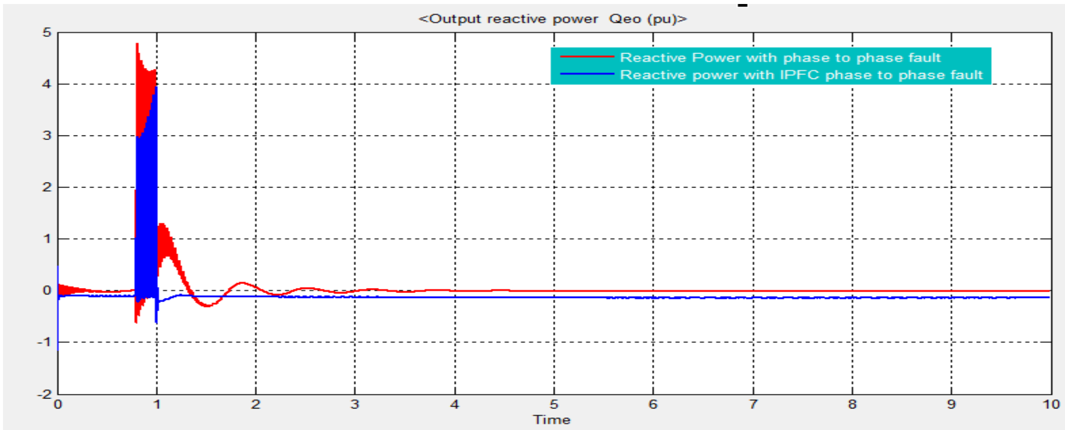

Figure 4-22: Simulation result of reactive power phase to phase fault

Figure 4.22 shows that the reactive power of the synchronous generator. From the simulation result it is observed that the oscillation magnitude is high around 4.8 p.u during the fault and oscillation is return to stable after 4.5 sec. the oscillation rise about 4.5 p.u during line to line fault when IPFC is connected and immediately turns to stable at 1second after the fault is cleared.

Excitation voltage of Tis Abay power generation system line to line fault

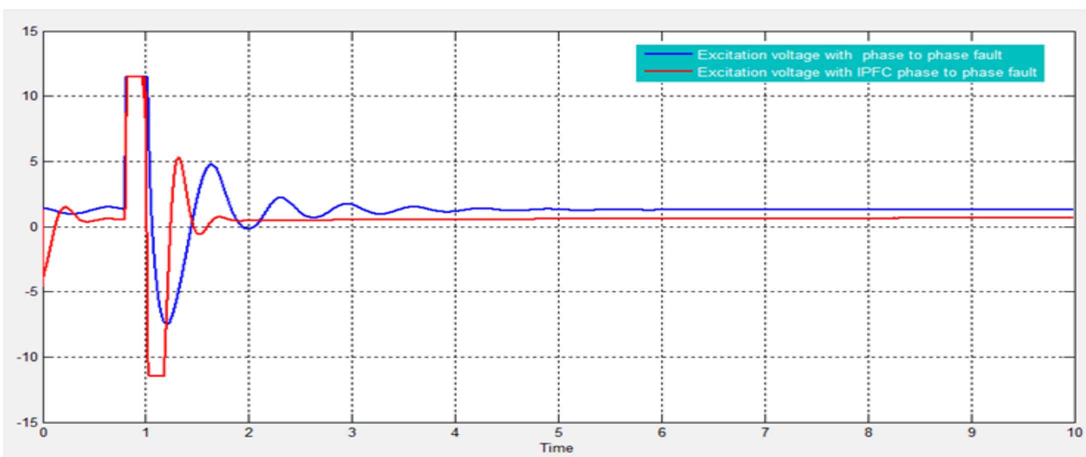

Figure 4-23: Simulation result of Excitation voltage phase to phase fault

Figure 4.23 shows the excitation voltage result of line to line fault both with out and with IPFC respectively. From the simulation result it is observed that the oscillation happened is the same for both during the fault. But using IPFC it is immediately stable after 1.5 second after the fault is cleared.

Terminal voltage of Tis Abay power generation system line to line fault

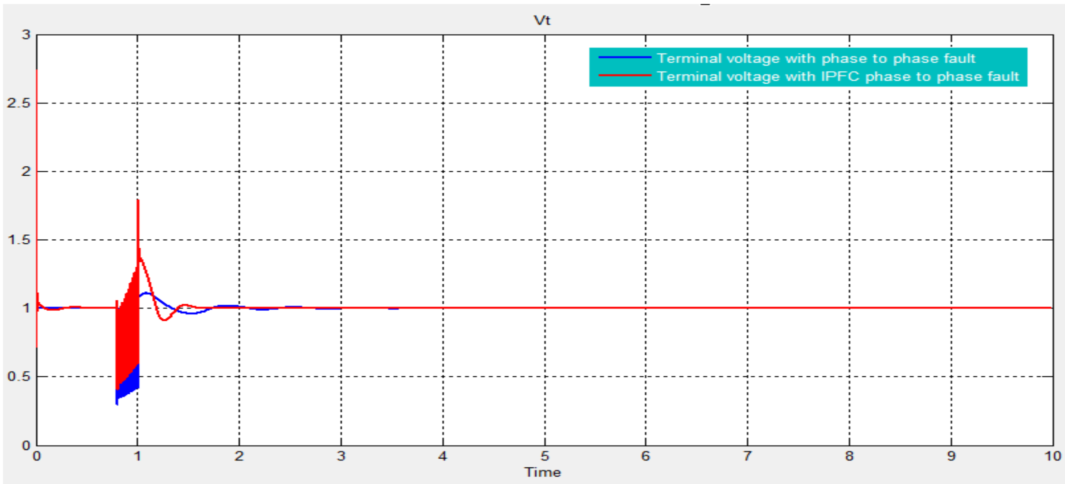

Figure 4-24: Matlab simulation result of terminal voltage phase to phase fault

Figure 4.24 shows the terminal voltage of the synchronous generator. The oscillation oscillates around 1.6 p.u and falls around 0.3 p.u. during line to line fault. It is stable after 2 second after the fault is cleared. When IPFC is connected it is stable immediately after 1.5 second after the fault is cleared. So IPFC improves the terminal voltage

Stator current of Tis Abay power generation system phase to phase fault

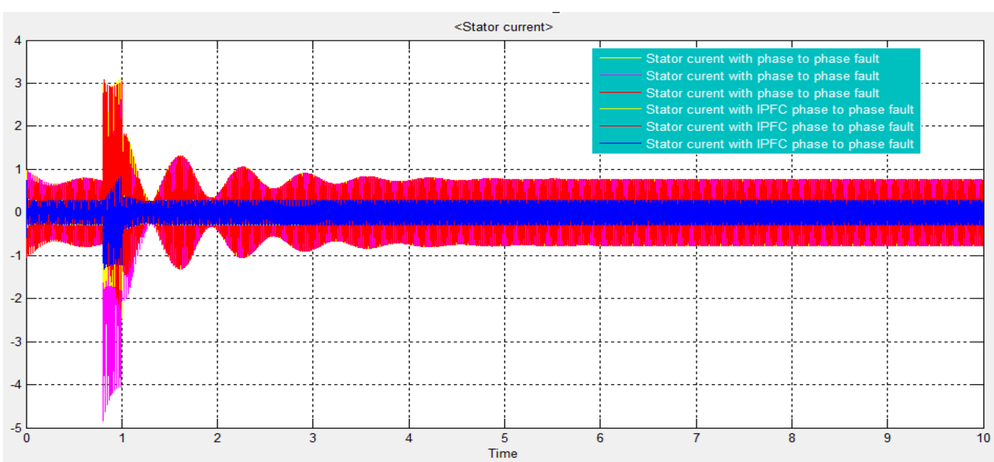

Figure 4-25: Simulation result of stator current phase to phase fault

From the simulation result shown in figure 4.25, the stator current oscillation increases about -5.0 to 3.0 during the line to line fault without IPFC. It takes more time about 4.5 returning to steady state. Also stator current oscillation increases -4.0 to 2.9 during the line to line fault when

IPFC is connected. It takes 1.2 second to stable quickly compared to with IPFC. So IPFC achieves the settling time quicker than conventional controller.

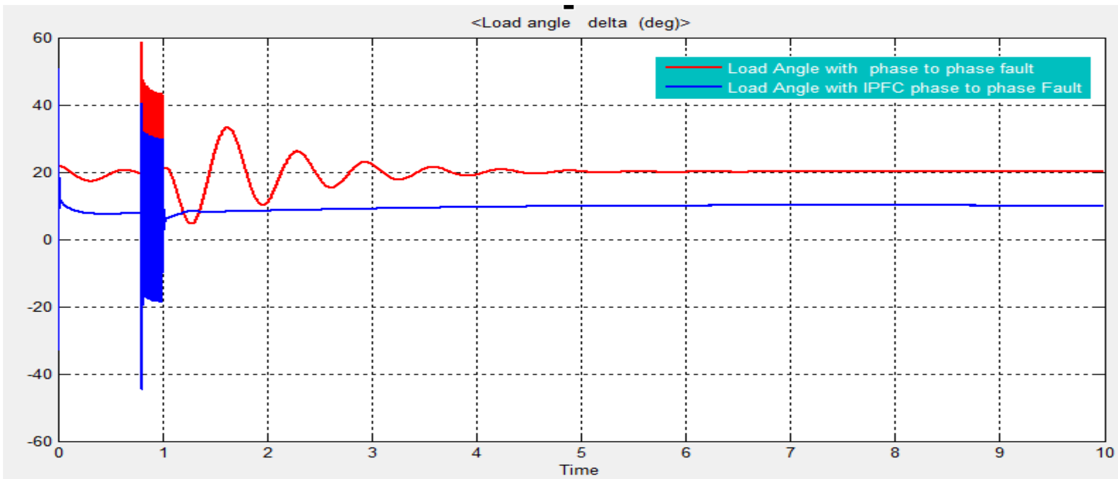

Figure 4-26: Simulation result of load angle phase to phase fault

From the Mat lab simulation of line to line fault, the load angle increases to a large value during the fault and decreases to also a small value after the fault is cleared. Figure 4.26 shows that the system without IPFC while subjected to a disturbance, the load angle is stable after 5 seconds. While with IPFC it is nearly take 1.2 second to be stable. So the settling time of IPFC is quicker than without IPFC.

CHAPTER FIVE

5 CONCLUSION AND RECOMMENDATION

5.1 Conclusion

This thesis shows the enhancement of transient stability by connecting IPFC to the transmission line of Tis Abay hydro power generation system for the purpose of transient stability in to the system during and after disturbances of three phases to ground and line to line fault.

The modeling and analysis of synchronous generator, HTG and excitation system controller have been done using MATLAB/SIMULINK software. Also the design and modeling of IPFC is developed and the simulation results of the system with and without IPFC are carried out due to the occurrence of fault (three phase to ground and line to line fault).

The load angle of the machine increases during faulted period and it decreases during post fault period. The settling time for the load angle is low for the system with IPFC for balanced and unbalanced faults.

When three phases to ground fault is occurred at a transmission line the load angle varies from -145^{o} to 60^{o} and the stability time starts at 4.5second without IPFC. When IPFC is connected, the load angle varies from -59^{o} to 40^{o} and stable at 1.2 second. Hence the load angle improved 70% to provide better damping oscillations and also reduce the oscillation time period. Also voltage magnitude is 1.0 p.u at the beginning of the simulation. It falls to about 0.3 p.u during the fault and returns to nominal after the fault is cleared. The quick response in terminal voltage is due to the fact that the excitation system output V_f can go as high as 11.5 p.u, which it does during the fault.

Also the simulation result shows that when three phases to ground fault is occurred the stability of the rotor speed is improved 64%, the active power is 79%, the reactive power is 80%, and excitation voltage is 70% by connecting IPFC to the system.

The simulation result observed considering line to line fault, the difference is insignificant change comparing to that of when three phase to ground fault happened with IPFC connected to the system.

The improvement of transient stability using the designed model by damping low frequency oscillation with less overshoot and shorter settling time shows the important of IPFC; also it increases system power transfer capability and prevents the equipment from damage.

5.2 Recommendation

Based on the studies and results found in this thesis, it is strongly recommended that Tis Abay II hydroelectric power generation systems should use IPFC to enhance transient stability when severe network disturbances and abnormalities occur in the system. Additional recommendation is also to safe electronic equipment from damaging to reduce power loss and to increase continuity of power supply to the customer.

5.3 Future Work

In this thesis, the transient stability improvement of a power system by using IPFC is studied. That can be extended by considering other FACT device and comparing the effectiveness in improving dynamic performance of Tis Abay II hydroelectric power generation systems and hence system stability with IPFC for the same study case by considering technical and economic benefits.

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APPENDIX

APPENDIX A: TYPICAL VALUES AND PARAMETERS RANGES OF TIS ABAY II HEPP

Table 1-A1: Turbine parameter

Manufacturer	China Wanbo Engineering corporation, Kvaerner (Hangzhou) power Equipment Co.Ltd,china
Type	Francis Turbine, HL (L 193751) -1.5 285
Rated power	36.830 Mw
Maximum head	60.0m
Rated head	53.2m
Minimum head	35.6m
Rated discharge	75.0m^3 /S
Speed	214.3rpm
Standard N0.	Gb/ T15468-1995

Table 2-A2: Generator parameter

Type	SF – 136- 28/5500
Standard No	GB 7894 - 87
Rated power	48MVA
Rated voltage	10.5KV
Rated current	2199.4 A
Frequency	50 HZ
Power factor	0.90
Connection	Y
Speed	214.3 RPM
Runway speed	445 rpm
Excitation voltage	14.5V
Excitation current	1085A

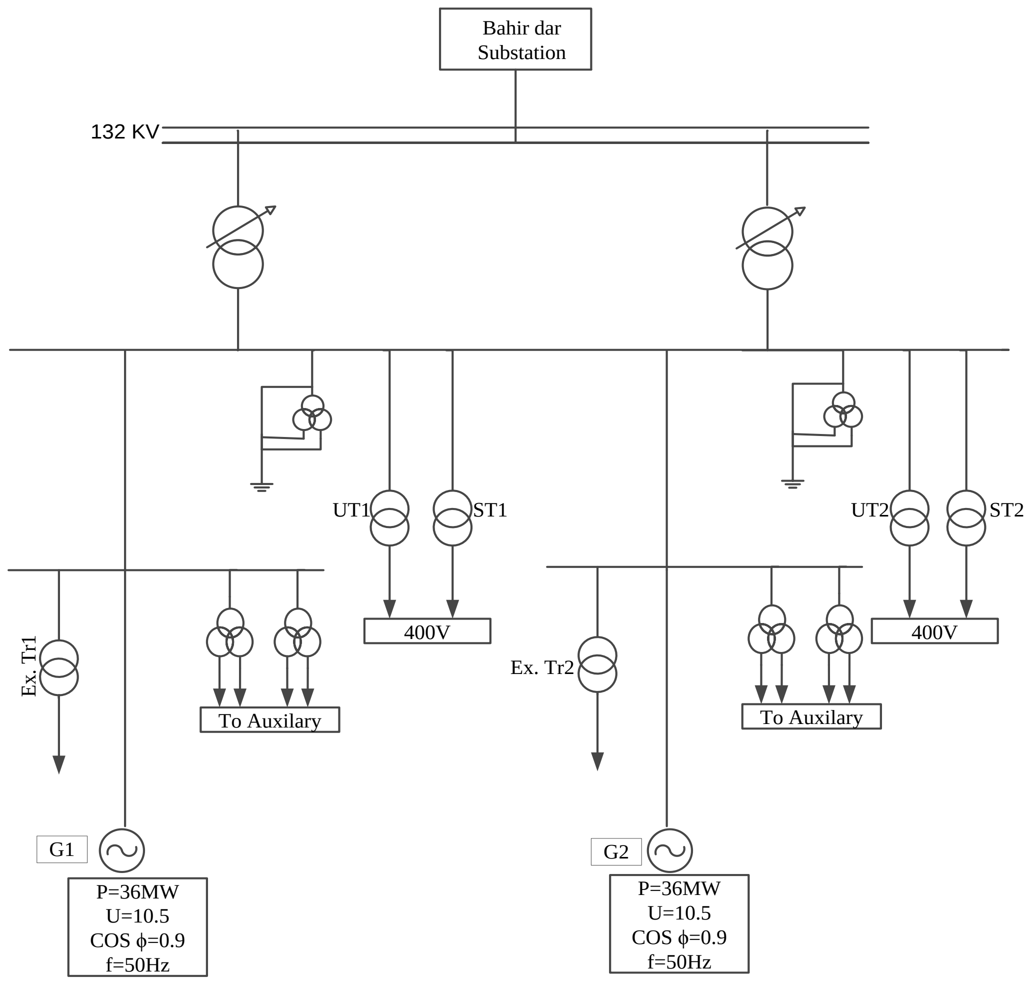
Table 3-A3: Governor parameter

Parameters	Parameter ranges	Data for simulation
Pilot valve and servomotor time constant TP	0.03- 0.05	0.05
Main servo time constant TG	0.2 – 0.4	0.2
Permanent droop RP	0.03 – 0.06	0.05
Temporary droop RT	0.2- 1.0	0.51
Reset time TR	5.0 - 25	9.35
PI controller Kp, Kd and Ki		0.6, 0.75 and 0.12

Table 4-A4: Electrical Characteristic

Short circuit ratio	≥1.0
Direct – axis synchronous reactance, saturated value (Xd) (Pu)	1.056
D – axis transient reactance, saturated value (X'd) pu	0.363
D – axis sub transient reactance, saturated value (X''d) (Pu)	0.241
Q – axis synchronous reactance, saturated value (Xq) (Pu)	0.721
Q - axis sub transient reactance, saturated value (X''q) (Pu)	0.249
Negative sequence reactance (X_2) (Pu)	0.245
Negative sequence resistance (R_2) (Pu)	0.01802
Zero sequence reactance (X_0) (Pu)	0.951
Zero sequence resistance (R_0) (Pu)	0.003875
Potier reactance (Xp) (Pu)	0.286
Armature winding direct current resistance (Ra) at 75^{o}C (Ω / phase)	0.010681
Positive sequence armature winding resistance (R_1) (Pu)	0.003875
Direct axis transient open circuit time constant (T'da) (S)	5.134
Direct axis transient short – circuit time constant (T'd) (S)	1.766
Direct axis sub transient short – circuit time constant (T"d) (S)	0.0516
Armature winding short – circuit time constant (Ta) (S)	0.201
Excitation winding direct – current resistance (Ra) at 75^{o}C (Ω / phase)	0.12693

APPENDIX B: SINGLE LINE DIAGRAM OF TIS ABAY GENERATION TO SUBSTATION



APPENDIX C: SIMULATION DIAGRAM OF IPFC