Investigation and Enhancement of Power System Stability Problem Using Appropriate FACTs Devices

Case Study: Gilgel-Gibe I to Jimma Transmission Line.

By

Sultan Idris Habib

A Thesis Submitted to School of Electrical Engineering and Computing
Department of Electrical Power and Control Engineering

Presented in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Electrical Power and Control Engineering
(Electrical Power Engineering)
Office of Graduate Studies

Adama Science and Technology University

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APPROVAL SHEET

We, the undersigned members of the board of examiners of final open defense by (Sultan Idris Habib) have read and evaluated his thesis entitled ***"investigation and enhancement of power system stability problem using appropriate FACTS devices"*** and examined the candidate thesis, to certify the thesis has been accepted

Sultan Idris		8/10/2020
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DECLARATION

I, the undersigned, declare that this thesis is my original work, and all the sources and materials used for the thesis work have been fully acknowledged.

Sultan Idris ______ ________________

Name of Student Signature

Place: Adama, Ethiopia

Date of Submission: ________________

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

Dr. Milkias Berhanu, Ph.D. ________________

Advisor’s Name Signature

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Sultan Idris

Adama. Ethiopia

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LIST OF SYMBOLS

ΔP_m	Change in mechanical power
t	Time
M	Angular momentum
PI	Proportional Integral
$\Delta\omega_r$	Per unit angular velocity
δ	Angular position of the rotor
$\Delta\varpi_r$	Per unit change in rotor speed
ΔP_e	Per unit change in electrical load power
ΔP_m	Per unit change in ballast load
ΔP_D	Per unit change in demand power
V_{LL}	Line voltage
R_{LL}	Ballast load resistance
D	Load damping constant
f	Frequency
ω_m	Angular velocity

LIST OF ABBREVIATION

AC	Alternating current
CCT	Critical clearing time
DC	Direct current
EAC	Equal area criteria
EHV	Extra high voltage
EMF	Electro motive force
FACT	Flexible Alternating Current transmission system
MVAR	Mega volt ampere
MW	Mega watt
PB	Positive Big
PSS	Power system stability
SMIB	Single machine infinite bus
SSR	Synchronous controlled resonance
TCSC	Thyrister controlled series compensation
TCR	Thyrister controlled rectifier
X_{TCSC}	Reactance of thyrister controlled Capacitor

ABSTRACT

Electric Power demand has increased substantially while the expansion of power generation and transmission systems has been severely limited due to scarce resources and environmental restrictions. As a result, some transmission lines are heavily loaded and the system stability is disturbed. Transient stability analysis has recently become a major issue in the operation of power systems; due to an increasing stress on power system networks. This problem requires evaluation of power system's ability to withstand disturbances while maintaining the reliability and quality of power service. An equal area criterion is one of the techniques which used to examine the stability of single machine connected to infinite bus without solving swing equation. However, Thyristor Controlled Series Capacitor (TCSC) is a variable capacitive and inductive reactance device that can be used to provide series compensation in power transmission line. In this thesis the power system from Gilgel-Gibe I to Jimma town substation is modeled with the inclusion and absence of TCSC for transient stability analysis. The simulation is carried out using MATLAB-Simulink software based on the actual parameters of the case study for result analysis and its discussions. Accordingly, the output of the simulation result shows that after the application of three phase fault for system without TCSC the active and reactive power oscillation is very high and power transfer capability is less. The voltage at the grid side reduced to zero and current is highly increased this results zero power transfer capability of the transmission line until the breaker clear the fault. After the fault is cleared the power transfer capability is less than before the fault happened on the system. However by changing the firing angle of the thyristor controlled reactor in decreasing mode comes with the reduction of the system impedance. This is further indicated with an increment of active and reactive power with slight oscillation, and power transfer capability of transmission line is improved. Particularly, the performance of TCSC is analyzed and the best firing angle for the reduction of the system impedance is obtained around 75^{o}.

Key words: Equal area criteria, FACTS Devices, MATLAB-Simulink, Power system stability, TCSC, Transient Stability.

CHAPTER ONE

INTRODUCTION

1.1 Background

Power system consists of three stages known as generation, transmission, and distribution. In the first stage the electric power is generated mostly using synchronous generators. Then the voltage level is raised using step up transformers before the power is transmitted in order to reduce the line current which consequently reduces losses of power in transmission line. After the transmission, the voltage is step down using step down transformers in order to be distributed according to the need of the customer. Power systems are designed to provide continuous Power supply that maintains voltage stability. However, due to undesired events, such as lightning, accidents or any other unpredictable events like short circuits between the phase wires of the transmission lines or between the phase wire and the ground which may occur is called fault the power system is disturbed. This disturbance may cause an imbalance between the generation and demand. If the fault persists and is not cleared in pre-specified time frame, it may cause severe damages to the equipment's which in turn may lead power loss and power outage. Therefore, protective equipment's are installed to detect faults and clear/isolate faulted parts of the power system as quickly as possible before the fault energy is propagated to the rest of the system[1].

Random changes in loads are taking place at all the times, with the subsequent adjustments of generation. We may look at any of these as a change from one equilibrium state to another. Synchronism frequently may be lost in that transition period, or growing oscillations which occur over a transmission line and eventually leading to its tripping. These problems must be studied by the power system engineer and fall under the heading of "power system stability". The tendency of a power system to develop restoring forces equal to or greater than the disturbing forces to maintain the state of equilibrium is known as "Stability". Stability phenomenon is a single problem associated with various forms of instabilities in the power system due to the high dimensionality and complexity of power system constructions and behaviors [2][3].

The electrical power system is a highly non-linear system that operates in a continuously changing environment. Key operating parameters like loads, generator outputs persistently change whenever it is subjected to any transient disturbance.

The stability of the power system depends on the initial operating conditions as well as the nature of the disturbance. The stability of power system is defined as the ability of a power system to return to its normal operation after having been subjected to some forms of disturbance. This is to regain an acceptable state of operating equilibrium after being subjected to a physical disturbance [4].

Generally, power systems are subjected to a wide range of disturbances which, are categorized into small and large. The small disturbances are in the form of load changes that occur continually whereas, the large disturbances are in the form of sudden change in the application of large loads, and removal of large loads and faults. The system must be able to adjust these changes to operate satisfactorily and successfully meeting the load demand. It must also be capable of coping disturbances of severe nature; such as a short circuit on a transmission line or loss of a generator [5]. Normally, a large disturbance sometimes can lead to structural changes in the power system due to the isolation of the faulted elements.

The definition of stability applies to all components of an interconnected power system as a whole. However, often the stability of a particular component or group of components which, plays a strong and significant role in the overall stability of the power system has also been considered. The stability performance of an interconnected power system which is generally affected by the dynamic characteristics of the machine whenever, subjected to disturbances such as quick change in electric load, occurrence of fault etc. These physical disturbances sometimes cause large variations in frequency, voltage, power flows, and other system constraints. These variations, thereby invoking the actions of processes, controls, and protections system that are incompletely and inappropriately modeled in conventional stability studies [4]. Thus, comprehensive and precise modeling of these processes, controls and protections are essential to diagnose the systems problem.

The transient stability studies involve the determination of whether or not synchronism is maintained after the machine has been subjected to severe disturbance. In most disturbances oscillations are of large magnitude that linearization is not permissible and the nonlinear swing equation must be solved [5][6].

The need for a new solutions and opportunities are important and critical. Flexible Alternating Current Transmission Systems (FACTS) devices have come to save this situation to some extent.

FACTS devices are used to increase the transmission line capacity and improve the stability of dynamic behavior of the machine.

The main advantage of FACTS devices are reactive power compensation, voltage control and power flow control. Due to their controllable power electronics, FACTS devices always provide fast control actions in comparison to conventional devices [7]

This thesis work mainly focuses on the stability of power system by using thyristor controlled series capacitor (TCSC) which allows rapid and continuous changes of the transmission line impedance by changing the firing angles of thyristor controlled reactor. It has great application potential in accurately regulating the power flow on the transmission line, damping power oscillations and improving transient stability. For this purpose, an approach for the appropriate modeling of the power system for interconnected scheme and its associated TCSC using MATLAB SIMULINK is proposed.

1.2 Theoretical background of the study Area

The generation of the south west region (Gilgel-Gibe I) has three different feeders lines. One feeder lines having stepped up voltage of 132kV goes to Jimma town substation and then distributed to different places after it has stepped down. The other two feeder lines having stepped up voltage of 230kV goes to Sebeta and Gefersa substation. There are three generator having 13.8kV and three transformers having a nominal power of 73MVA rating capacity and the fourth transformers having a capacity of 40MVA. The three transformers are step up but one transformer is called auto transformer which step down the 230kV to 132kV then send to Jimma substation. In Gilgel-Gibe I to Jimma transmission line different types of faults happen which leads the system to be disturbed. In terms of frequency of occurrence line to ground fault happen mostly but compared to three phase faults it’s consequences is less that this thesis focuses on three phase fault.

1.3 Statement of the problem

Loads connected to the generator require a uniform and an uninterrupted supply of electrical power in order to maintain the power system stability. This cannot be achieved without the use of compensating devices like FACTS devices. On the other hand, an occurrence of fault may lead the power system to be interrupted and the connected electrical machines to fall out of synchronism. This can be resulted with huge and unnecessary consequences unless and otherwise the system cannot sustain till the fault is cleared. If the oscillation in rotor angle around the final position go on an increasing mode and the change in angular speed during transient condition also goes increasing, then system never comes to its final steady state position. Thus, generally the power system stability analysis together with the compensation techniques is very important aspects in power engineering fields since; the system is exposed to different kinds of disturbances and loss of huge energy. Therefore, the aforementioned point's leads to the modeling and design of TCSC for the purpose of power system compensation and minimization of the above mentioned drawbacks.

1.4 Objectives of the thesis

1.4.1 General Objective

The main objective of this thesis is an investigation and enhancement of power system stability problem by using appropriate FACTS devices.

1.4.2 Specific objectives

In order to achieve the general objectives, the thesis has been outlined with the following specific objectives are to:

- Model and simulate the power system from Gilgel-Gibe I to jimma town substation using MATLAB-Simulink with and without fault under the absence and inclusion of TCSC
- Design and model of swing equation
- Design and model of TCSC
- Analyze equal area criteria for different cases

1.5 Significance of the study

The following points can be briefed as significances of the thesis work..

- Increase Power transfer capability and reduce oscillation.
- It will provide quality power for the customers
- Increasing of power efficiency
- To have reliable power system.
- To have secured power system
- Loss minimization and Significant energy saving
- To investigate the power quality disturbances

1.6 Scope of the Thesis

The aim of this thesis is to improve the power system transient stability problem, and reducing oscillation in active and reactive power using TCSC device and increasing the power transfer capability between the systems. Showing and implementing effects of fault location in power system stability with MATLAB Simulink using Sim-Power systems tool.

1.7 Methodology and tools

1.7.1 Methodology

The research methodology of this thesis involves a number of different tasks that are performed to lead towards its completion. The first task is to describe the statement of the problem and define the objectives of the research. This is followed by the literature review where all the theoretical information regarding power system stability is investigated. A comparison of previous similar research works is also presented. A brief description on the TCSC is then presented. Following, a detail mathematical modeling of swing equation and equal area criteria is presented. For the selected FACTs device technology, TCSCs is designed for controlling the active and reactive power in order to improve transient stability problems. This is followed by reducing the system reactance and decreasing the angle between end line voltages.

Simulation studies are carried out for different fault location to show the most sever fault location for power system stability enhancement.

The final stage is the conclusion based on the research findings. A flow chart representing the methodology of the thesis is shown in Fig.1. 1.

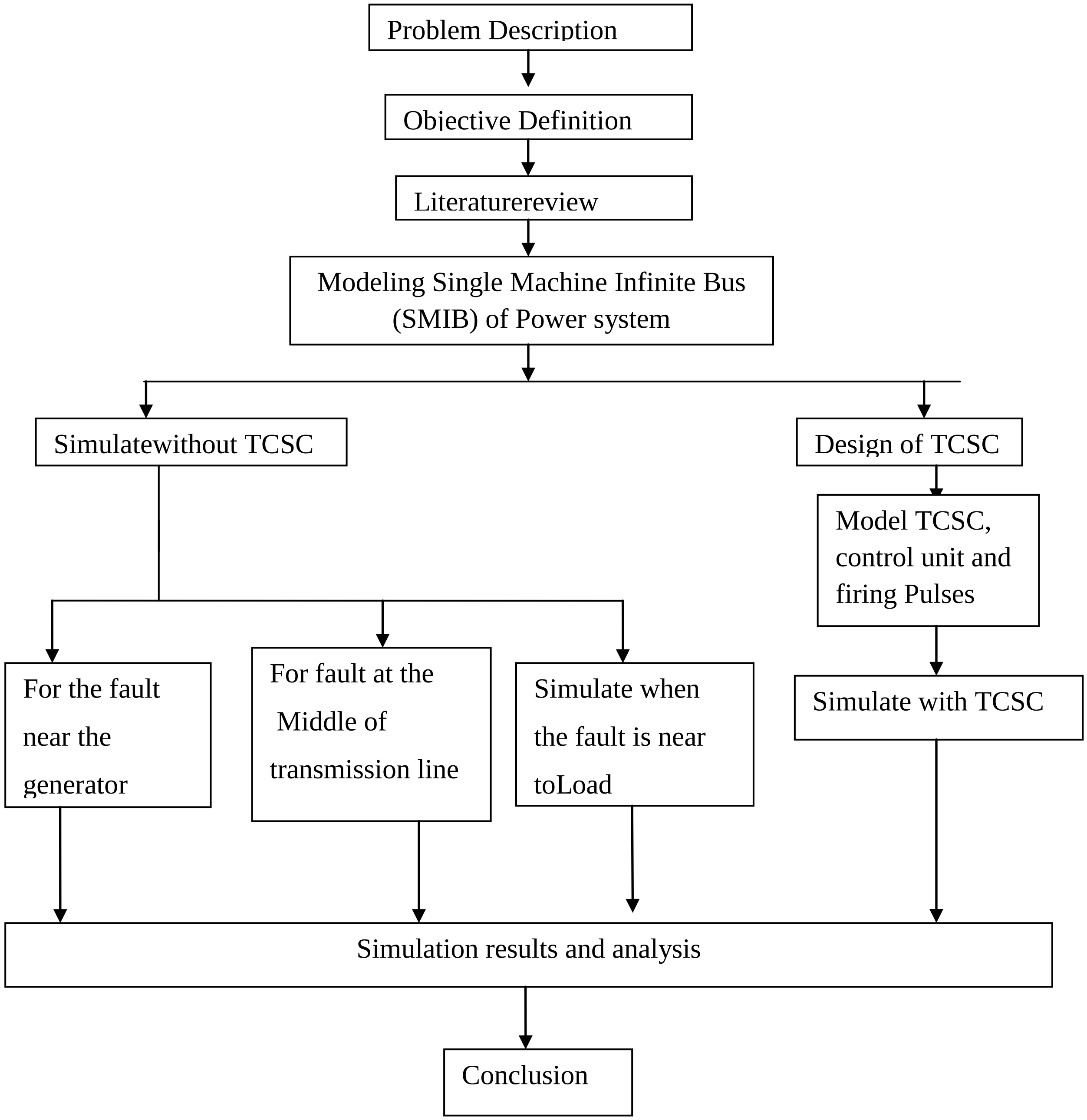


Fig.1. 1: Flow chart of the research methodology of the thesis.

1.7.2 Tools used

- MATLAB Simulation
- Thyrister controlled series capacitor (TCSC)
- Bus bar

- Transmissions lines
- Transformer
- Capacitor
- Control unit
- TCR

1.8 Thesis outline

The thesis is organized into five chapters.

Chapter one presents the introduction, statement of the problem, objectives of the study and the methodology leading towards the completion of the thesis.

The second chapter discusses about review in power system stability, related works and Finally, Thyrister Controlled Series Capacitors (TCSC) are discussed in brief.

Chapter three deals the design of power system, modeling of the Synchronous generator, transformer and loads are described in this chapter. Internal sub system of TCSC; swing equation for Synchronous generator are also presented in this chapter. Different Load configurations and modeling of the load are discussed in this chapter.

Chapter four discusses the simulation results and discussion

Chapter five presents ‘the conclusions and Recommendations for future work.

CHAPTER TWO

THEOROTICAL BACKGROUND AND LITERATURE REVIEW

2.1 LITERATURE REVIEW

Power system stability is a very important issue for guaranteeing continuous and sustainable power to the load centers. Power system stability also provides acceptable operating points under normal operating conditions and adjusts the new acceptable operating points as the power system suffers abnormalities like, faults of different types or even under load variations [8][9].

Due to many factors electric power systems are extremely complex. It consists of uncounted numbers of facilities and structures, systems and subsystems, components and equipment, and the complex interactions. The interactions are physical interactions, operational interactions, and administrative interactions [10] [11].

Transient stability involves the response to large disturbances, which may cause large changes in rotor speeds, power angles and power transfers. Transient stability is a fast phenomenon usually evident within a few second [12].

2.2 The Development of Power system stability problems

During the early part of the 20th century, small oscillations in synchronous generators became a problem for power system engineers; this phenomenon comes to be known as ‘hunting’. It was particularly noticeable when a generator was synchronized to the system through a long line. With the introduction of damper windings, the problem of hunting was significantly reduced.

Power system stability has been recognized as an important problem for secure system operation in 1920where as, it is tested for practical power system in 1926 [5][13]. Initially stability problems occurred in distant power plants feeding load over expanded transmission lines. This transmission line uses slow exciters and non-continuously acting voltage controllers due to which, power transfer capability was often restricted due to inadequate synchronizing torque.

As power systems have evolved through continuing growth of interconnections, use of new technologies and controlling scheme increases systems performance operation. There are different forms of system instability have emerged like voltage instability, angle instability and frequency instability. A clear understanding of different types of instability and their interrelationship is necessary for the satisfactory design and operation of power systems.

In the 1960s, the problem of small oscillations in power systems presented problems in terms of system operation. These oscillations have been described as dynamic instability, small oscillations or low frequency oscillations in power systems. This chapter reviews an approaches proposed for power oscillation damping [13].

The basic concepts of power system stability and the classification of the oscillations are analyzed by Prabha Kundur et al (1994). Present-day power systems are being operated under increasingly stressed conditions. Increased competition, open transmission access, and construction and environmental constraints are shaping the operation of electric power systems in new ways that present greater challenges for maintaining the system stability) [6] [11].

Power system stability is a major challenge for engineers from many years. Equal area criterion (EAC) methods are designed to solve this problem and so models become superior and economical. The next significant test on the way of stability improvement was the development of network analyzer, which was proficient of power flow investigation of multi-machine power systems in 1930 [12]. This system has a drawback that the system dynamic had to explain by explaining the swing equation using step-by-step numerical integration.

After the invention of electronic analog computer in 1950 detailed modeling of the synchronous machine, excitation system and speed governor became easier. Later on with evolution in digital computers about 1956, the first digital program for power system stability investigation was returned. In the later decades various systems of power system stability were designed in Canada and United States. In earlier days efforts were made for optimal linear regulator design of a multi-machine power system through a computational algorithm based on the matrix sign function theory, which give solutions without the evaluation of the system Eigen values (1972)

A computer program has been designed to incorporate the developed computational techniques, which are based on the matrix sign function theory and have been obtained by the optimal controllers and the dynamic responses of the power system [14].

Later on a technique for designing variable structure controllers (VSCs) to damp out multimodal oscillations in a multi machine power system was proposed. Along with an approach of incorporating nonlinearities in the system operation at the design stage is analyzed. Samarasinghe and N. Pahalawaththa show the possibility of achieving a robust design using a simple linear model of power systems [7][15].

The system demonstrate the effectiveness of the VSC through a number of experiments results in showing that a VSC performs better than a conventional power system stabilizer and both types of controllers on different units in the system co-operate in a positive manner in damping oscillations.

After that in 2004 N. S.D. Arrifano, V. A. Oliveira, R. A. Ramos design method and application of fuzzy power system stabilizers for electrical power systems subject to random abrupt variations of loads are considered [5]. Here, the control design method uses recently developed techniques based on linear matrix inequalities with damping and control input constraints for fuzzy logic control design was proposed [9] [16].

In 2007 system was designed for the study of dynamic behavior and transient stability of the single-machine infinite-bus (SMIB) with the use of Eigenvalue analysis. To enhance the system stability, speed deviation ($\Delta\omega$) and acceleration ($\Delta\alpha$) of the rotor of synchronous generator were taken as the input to the fuzzy logic controller which has significant effects on damping of the generator shaft mechanical oscillations. An alternative approach on designing of PSS for Single machine connected to infinite bus (SMIB) system based on optimal control (OP) techniques was proposed in later days. The simulation technique was used for analyzing small signal stability characteristics of steady state operating condition following the loss of a transmission line. The focus of the system was controlling the disturbance and showing the performance of the technique used [9][17].

Researches' were done for designing power system stability of an interconnected power system. In this system, information available at the high voltage bus of the step-up transformer is used to set up a modified model. This model is used to decide the structure of the PSS compensator and tune its parameters at each machine in only those signals that are available at the generating station [8]. Now a day's advanced technology is emerging which has fast controlling scheme and has high capability to withstand the disturbances in the power system.

2.3 Power system stability

Power system stability is the ability of electric power system to regain a state of operating equilibrium after, having been subjected to a physical disturbance. The power system is a highly nonlinear system that operates in a constantly changing environment; loads, generator outputs and key operating parameters change continually.

When Subjected to a disturbance, the stability of the system depends on the initial operating condition as well as the nature of the disturbance. Stability of an electric power system is thus a property of the system motion around an equilibrium set.

Power systems are subjected to a wide range of disturbances, small and large. Small disturbances are in the form of load changes that occur continually. The power system must be able to adjust the changing conditions and operate satisfactorily. Power systems must also be able to survive numerous disturbances of 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 [18].

At an equilibrium set, a power system may be stable for a given (large) physical disturbance, and unstable for another. It is impractical and uneconomical to design power systems to be stable for every possible disturbance. The design contingencies are selected on the basis they have a reasonably high probability of occurrence [14] [19].

A stable equilibrium set thus has a finite region of attraction; the larger the region, the more robust the system with respect to large disturbances. The region of attraction changes with the operating condition of the power system [9].

Stability studies are classified into three types depending upon the nature and order of magnitude of disturbance. These are:

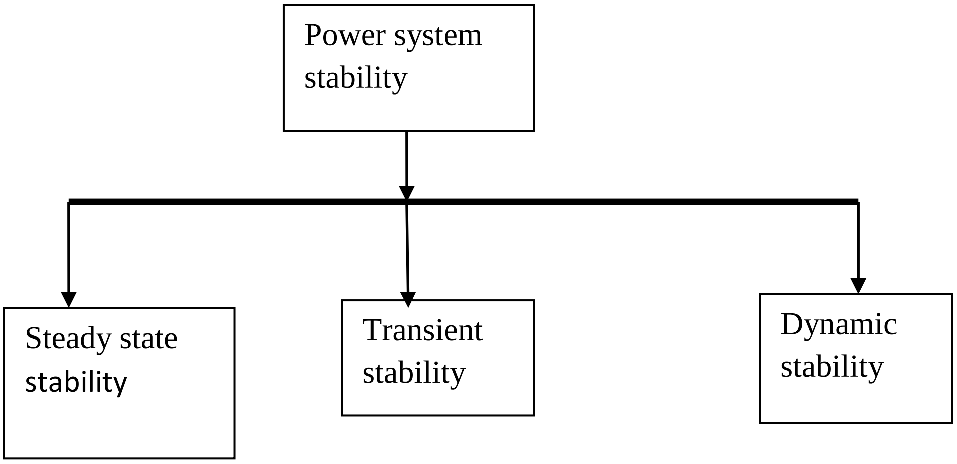


Fig.2. 1: Types of power system stability [3]

1. Steady-state stability: .refers to the ability of the power system to regain synchronism after small and slow disturbance, such as gradual power change.

2. **Transient stability**: is an ability of the power system to regain synchronism after a large disturbance. This occurs due to sudden change in the application or removal of large load, line switching operation due to fault on the system, sudden outage of the line or loss of excitation.

3. **Dynamic stability**: it refers to the stability of a power system subject to a relatively small and sudden disturbance

2.4 Stability Limits

The stability limit is the maximum amount of power that can be transferred in the network between source and loads without loss of synchronism.

The steady-state stability limit:-Is the maximum amount of power that can be transferred from the source to the load without the system becoming unstable when, the load is increased gradually under steady state condition.

Transient stability limit: - Is the maximum power that can be transferred without the system becoming unstable when a sudden or large disturbance occurs

2.5 Categories of power system Stability problems

The classification of power system stability proposed here is based on the following considerations [11]:

- 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.

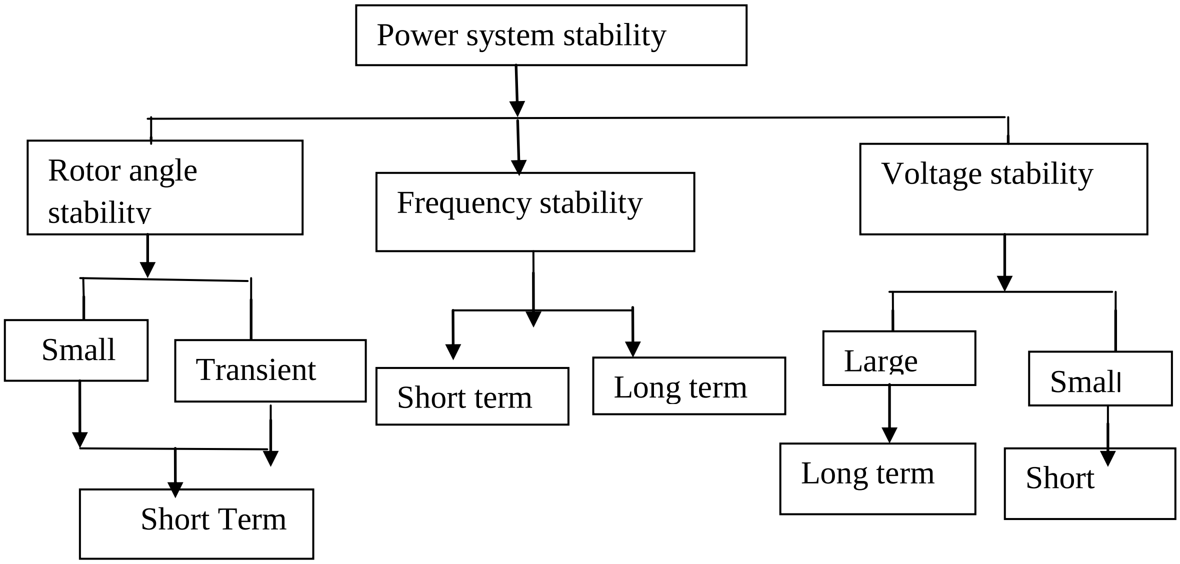


Fig.2. 2: Classification of power system stability [11]

2.5.1 Rotor angle stability

It is the ability of synchronous machines of an interconnected power system to remain in synchronism after being subjected to some form of disturbance. It depends on the ability to maintain/restore equilibrium between electromagnetic torque and mechanical torque of each synchronous machine in the system.

Small-disturbance (or small-signal) rotor angle stability is concerned with the ability of the power system to maintain synchronism under small disturbances. The disturbances are considered to be sufficiently small that linearization of system equations is permissible for purposes of analysis [16][19].

Transient stability is commonly concerned with the ability of interconnected power system to maintain synchronism when subjected to a severe disturbance, such as a short circuit on a transmission line. The resulting system response involves large excursions of generator rotor angles and is influenced by the nonlinear power-angle relationship. Transient stability depends on both the initial operating state of the system and the severity of the disturbance. Instability is usually in the form of a periodic angular separation due to insufficient synchronizing torque, manifesting as first swing instability.

However, in large power systems, transient instability may not always occur as first swing instability it may also be superposition of a slow inertia swing mode and a local-plant swing mode causing a large excursion of rotor angle beyond the first swing [11].

It could also be a result of nonlinear effects affecting a single model causing instability beyond the first swing. Factors affecting transient stability

- Post fault reactance
- Duration of fault
- Inertia of the machine
- Generator internal voltage
- Loading status of generator before disturbance
- Internal reactance of generator
- Generator output power during disturbance

2.5.2 Voltage stability

Voltage stability is the ability of a power system to maintain steady state voltages at all buses in the system after being subjected to disturbance for a given initial operating condition. 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 violate field current limit [7].

Short-term voltage stability: involves dynamics of fast acting load components such as induction motors, electronically controlled loads, and HVDC converters. The study period of interest is in the order of several seconds, and analysis requires solution of appropriate system differential equations;

Long-term voltage stability: involves slower acting equipment such as tap-changing transformers, thermostatically controlled loads, and generator current limiters. The study period of interest may extend to several or many minutes, and long-term simulations are required for analysis of system dynamic performance [1][8][9]. Stability is usually determined by the resulting outage of equipment, rather than the severity of the initial disturbance.

2.5.3 Frequency stability

Frequency stability refers to the ability of a power system to maintain steady state frequency following a severe disturbance resulting in a significant imbalance between generation and load [13][20]. A typical cause for frequency instability is the loss of generation, which results in sudden unbalance between the generation and load.

The control schemes of frequency deviation used to recover the system frequency without the need for customer load shedding achieved. This is by instantaneously activating the spinning reserve of the remaining units to supply the load demand in order to raise the frequency. The controllers of all activated generators alter the power delivered by the generators until a balance between power output and consumption is re-established. Spinning reserve to be utilized by the primary control should be uniformly distributed around the system. Then the reserve will come from a variety of locations and the risk of overloading some transmission line will be minimized. The frequency stabilization obtained and maintained at a steady state value, but differs from the frequency set point. The Secondary control, in the portion of the system contains power unbalance, which will take over the remaining frequency and power deviation after 15 to 30 seconds to return the initial frequency and restore the power balance in each control area.

2.6 Equal Area Criterion

Equal area criterion of stability is a technique by which the stability of a single machine connected to infinite bus can be examined under transient condition without solving the swing equation. To study transient stability we use equal area criteria; it is a quick prediction of power system stability. Equal area criterion is applicable only when, one machine swings with respect to an infinite bus [21]. So equal area criterion cannot be used directly in system where three or more machine is represented. For studying the transient stability of multi-machine, the swing equation for the system should be solved. To do this the following should be done:

- Reducing the system network to a single equivalent circuit.
- Determining the transfer-point, and driving–point impedance for circuit condition of fault-on and fault-off.
- Determining the initial condition and power flow equation for the various subsequent transient conditions.
- Determining the acceleration torque constant for each machine group.

The synchronous machine is operating in steady state delivers a power P_e equal to P_m when there is a no fault occurs in the system. If there is a faults opening up of the circuit breakers in the faulted section subsequently clears the fault. The circuit breakers take about 5/6 cycles to open and the subsequent post-fault transient last for another few cycles. For all practical purpose the mechanical power is remains constant during period of electrical transients occur. The transient stability study therefore concentrates on the ability of the power system to recover from the fault and deliver the constant power P_m with a possible new load angle δ[13].

Suppose the system is operating in the steady state delivering a power of P_m at an angle of δ0, due to mal-function of the line, circuit breakers opens which reduces the real power transferred to zero. Since P_m remains constant, the accelerating power P_a becomes equal to P_m. The difference in the power gives rise to the rate of change of stored kinetic energy in the rotor masses. Thus the rotor will accelerate under the constant influence of non-zero accelerating power and hence the load angle will increase. Now suppose the circuit breaker re-closes at an angle δ_c. The power will then revert back to the normal operating curve. At that point, the electrical power will be more than the mechanical power and the accelerating power will be negative. This will cause the machine to decelerate. However, due to the inertia of the rotor masses, the load angle will still keep on increasing. The increase in this angle may eventually stop and the rotor may start decelerating, otherwise the system will lose synchronism. The power angle curve is shown in Fig.2. 3

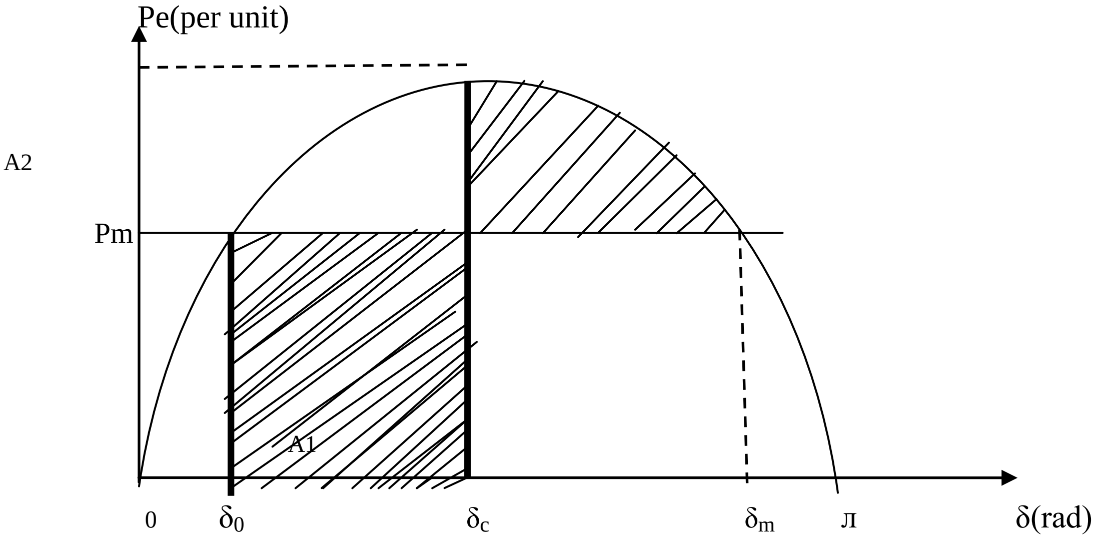


Fig.2. 3: Power angle curves for equal area criterion [22]

From swing equation of the generator

$$2H\omega_s \frac{d^2\delta}{dt^2} = P_m - P_e \tag{2.1}$$

Hence, multiplying both sides of the equation by $\frac{d\delta}{dt}$ and rearranging

$$\frac{H}{\omega_s}\frac{d}{dt}(\frac{d\delta}{dt})^2 = P_m - P_e \tag{2.2}$$

Multiplying both sides of the above equation by dt and then integrating between two arbitrary angles $\delta_o$and δ_c

$$\frac{H}{\omega_s}(\frac{d\delta}{dt})^2 = \int_{\delta o}^{\delta c} P_m - P_e \tag{2.3}$$

Now suppose the generator is at rest at $\delta_0$then $d\delta/_{dt}$ = 0. First the machine start accelerating and if the fault occurs, the machine become decelerating. Once the fault is cleared, the machine keeps on accelerating before it reaches its peak at δ_c, at which again$d\delta/_{dt}$= 0. Thus the area of acceleration in the above figure is

$$\mathrm{A}_1 = \int_{\delta \mathrm{o}}^{\delta \mathrm{c}} (P_m - P_e) d\delta = 0 \tag{2.4}$$

In this formula if the value of δ_c is increasing and condition is not satisfied then the system is not stable. But, if the condition of equation (2.3) is satisfied before the angle reaches the values of δ_c then the system is stable.

The area of acceleration is given by A_1while the area of deceleration is given by A_2. This is given by:

$$\mathrm{A}_2 = \int_{\delta c}^{\delta m} (P_e - P_m) d\delta = 0 \tag{2.5}$$

Now consider the case when, the line is reclosed at δ_c such that the area of acceleration is larger than the area of deceleration. i.e, $A_1>A_2$The generator load angle will then cross the point δ_m, beyond which the electrical power will be less than the mechanical power forcing the accelerating power to be positive. The generator will therefore start accelerating before it slows down completely and will eventually become unstable.

If, on the other hand, $A_1 < A_2$ i.e, the decelerating area is larger than the accelerating area, the machine will decelerate completely before accelerating again. The rotor inertia will force the subsequent acceleration and deceleration areas to be smaller than the first ones and the machine will eventually attain the steady state.

If the two areas are equal, $A_1 = A_2$ then the accelerating area is equal to decelerating area and this is defines the boundary of the stability limit. The clearing angle δ_c for this mode is called the critical clearing angle and is denoted by δ_{cr}. We then get from Fig .2.3 by substituting δ_c in to δ_{cr} as follows:

$$A_1 = \int_{\delta c}^{\delta cr} (P_m - P_e) d\delta = \int_{\delta cr}^{\delta m} (P_e - P_m) d\delta \qquad (2.6)$$

2.6.1 How to find critical angle and critical clearing time?

For the power system to be transiently stable after a large disturbance; the disturbance has to be removed or isolated in a short period of time. The time duration between the instant of disturbance initiation and the instant of disturbance removal is termed as the fault clearing time.This fault clearing time primarily constitutes the time taken by the relays and the circuit breakers to operate after a disturbance has been detected.

The upper bound on the fault clearing time is termed as the critical clearing time (CCT). The CCT is the maximum time between the disturbance initiation and its fault clearing time such that the power system is transiently stable.

If a fualts occurs in a system δ begins to increase under the influence of posative accelarating power and the system becomes unstable.There is critical angle within which, the fualt must be cleraed for the system to remain stable and the equl area crateria is to be satisified; this angle is known as critical clearing angle.Since it is interested to find out the maximum time that the circuit breakers may take for opening, this is should be more concerned about the critical clearing time rather than clearing angle. Further theclearing angle is independent of the generalized inertia constant;the critical clearing time, however, is dependent on inertia constant and will vary as this parameter varies. To obtain a description for the critical clearing time, let us consider the period during which the fault occurs. We then have $P_e = 0$ and from swing equation

$$\frac{\omega_s}{2H}\frac{d^2\delta}{dt^2} = P_m - P_e \tag{2.7}$$

Integrating the above equation with the initial acceleration being zero

$$\frac{d\delta}{dt} = \int_0^t \omega_s \frac{1}{2H} P_m dt = \frac{\omega_s}{2H} Pmt \tag{2.8}$$

Further integration will lead to

$$\delta = \int_0^t \omega_s \frac{1}{2H} P_m t dt = \frac{\omega_s}{4H} P_m t^2 + \delta_o \tag{2.9}$$

Replacing δ by δ_{cr} and t by t_{cr} in the above equation then the criticalclearing time is

$$t_{cr} = \sqrt{\frac{4H(\delta_{cr} - \delta_o)}{\omega_s P_m}} \tag{2.10}$$

2.7 Step by Step method of solving transient stability

The swing equation can be solved iterartevly with the step by step technique shown belown in figure(2.4). In the solution it is assumed that the accelarating power(P_a) and the relative rotor angle velocity ω_r are constant whithin each of succession of interval(top and midlle in Fig.2. 4 their values are then used to find the change in δ during each interval. The iterative procedure start with $P_{a(0+)}$ which we evaluate as

$$P_{a(0+)} = P_i - P_{m(0+)} \tag{2.11}$$

Then the swing equation writen as

$$\frac{d^2\delta}{dt^2} = \alpha_{(0+)} = \frac{P_{a(0+)} * \pi f}{H} \tag{2.12}$$

And the change in ω_r is given in (fig 2.4) by

$$\Delta\omega_r = \alpha_{(0+)}\Delta t \tag{2.13}$$

$$\omega_r = \omega_o + \Delta\omega_r = \omega_o + \alpha_{(0+)}\Delta t \tag{2.14}$$

The average value of ωr during the first interval is then

$$\omega_{ravg} = \omega_o + \frac{\Delta\omega_r}{2} \tag{2.15}$$

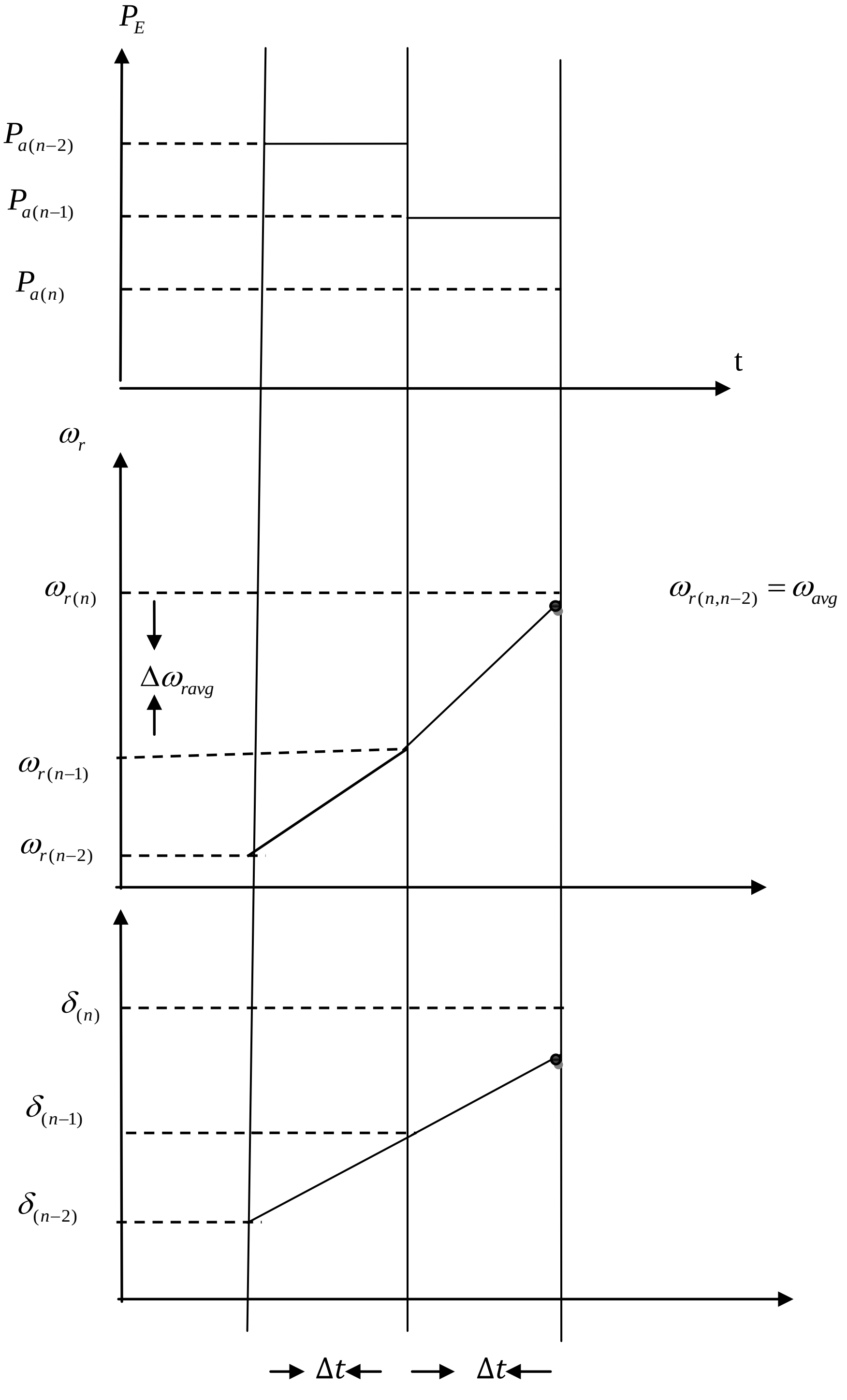


Fig.2. 4: Step by step methods to solve transient stability[13].

Similarly the change in the power angle for the first interval is

$$\Delta\delta_1 = \omega_{r(avg)} * \Delta t \tag{2.16}$$

Hence, $\delta_1 = \delta_0 + \Delta\delta_1$ (2.17)

Evaluation of P_a and ω_{ravg}

When using the step-by step technique P_a is assumed to be constant over the step interval and equals to its value at the beginning of the interval.Thus

$$P_0 = P_{a(n-1)} + \tag{2.18}$$

As shown in the fig 2.4. If a discontuinity occur during a step interval (such as might be caused by the clearing of the faults), the standard approach is to simply redefine the interval at that points so that the discontiunity occurs at the end (beginning) of step interval. The average speed over an interval is given as:

$$\omega_{r(n,n-1)} = \omega_{avg} = \frac{\omega_{r(n)} + \omega_{r(n-1)}}{2} \tag{2.19}$$

Algorithm for the iteration

Returning now to equation(2.16) we see that δ_1 gives us one point on the swing curve. The algorithm for the iterative process is as follows.

$$P_{a\,(n-1)} = P_i - P_{e\,(n-1)} \tag{2.20}$$

$$P_{e(n-1)} = \frac{E||V|\ \sin\delta_{(n-1)}}{X} \tag{2.21}$$

$$\alpha_{(n-1)} = \frac{P_{a(n-1)} * (180f)}{H} \tag{2.22}$$

$$\Delta\omega_{r(n)} = \alpha_{(n-1)}\ \Delta t \tag{2.23}$$

$$\omega_{r\,(n,n-1)} = \omega_{r(avg)} = \frac{\omega_{r(n-1)} + \Delta\omega_{(r(n)}}{2} \tag{2.24}$$

$$\Delta\delta_{(n)} = \omega_{r\,(n,n-1)}\ \Delta t \tag{2.25}$$

$$\delta_{(n)} = \delta_{(n-1)} + \Delta\delta_{(n)} \tag{2.26}$$

Point-by-Point Method: is always required to know the critical clearing time corresponding to critical clearing angle so as to design the operating times of the relay and circuit breaker so that time taken by them should be less than the critical clearing time for stable operation of the system.

The step-by-step or point-by point method is the conventional, approximate but proven method. This involves the calculation of the rotor angle as time is incremented. The accuracy of the solution depends upon the time increment used in the analysis.

2.8 Previous Works on Power system stability enhancement technique

Transient stability can be improved either by using machines of higher inertia or by connecting the synchronous motor to heavy flywheels. This model however cannot be used in practice for economic reason and reason of excessive rotor weight. On contrary the modern trend in generator design is to achieve more power from smaller machine and lighter rotor. However this trend is undesirable and not used from the point view of stability. A salient-pole generator operates at lower load angles and is therefore preferred over the cylindrical rotor generators for consideration of stability [9].

1. High speed fault clearing

Transient stability is improved by increasing the system voltage profile (i.e. raising E and V). Increasing the system voltage means the higher value of maximum power that can be transferred over the lines. Since the shaft power $P_s = P_{\max} \sin \delta$, therefore, for a given shaft power initial load angle δ_0 reduces with the increase in P_{max} and thereby increasing difference between the critical clearing angle and initial load angle. Thus the machine is allowed to rotate through large angle before it reaches the critical clearing angle which results in greater critical clearing time and the probability of maintaining stability[7][8].

2. Reduction in Transfer Reactance

Transient stability can also be improved by reducing the transfer reactance. The effect of reducing the transfer reactance means increase of P_{max} resulting to increase transient stability. The line reactance can be reduced by using more lines in parallel instead of a single line. Increasing power transfer means less available accelerating power, because the accelerating power is the difference between power input and power transferred. Lower accelerating power reduces the risk of instability. The use of bundled conductor lies also helps in reducing line reactance and improving stability. This method is helpful in maintaining the stability but needs the line to be parallel instead of single [14].

3. Using High Speed Circuit Breaker:

The best method of improving transient stability is the use of high-speed circuit breakers. The quicker a breaker operates, the faster the fault is removed from the system and better is the tendency of the system to restore to normal operating conditions. The use of high-speed breakers has materially improved the transient stability of the power system. High-speed breakers increase the decelerating area and decrease the accelerating area thereby, improves the stability. However the power transferred capability is less after the fault is cleared [20].

4. Automatic Reclosing

As the majority of faults on the transmission lines are transient in nature and are self-clearing and rapid switching so, isolation of the faulty lines followed by reclosing are quite helpful in maintaining stability. The modern circuit breaker technology has made it possible for a line fault clearing to be done as fast as in 2 cycles. On the occurrence of fault on the transmission line, the faulted line is de-energized to suppress the arc in the fault and then the circuit breaker recloses after suitable time interval [21]. Automatic reclosing increases the decelerating area and thus helps in improving stability but not flexible.

5. High neutral grounding impedance.

The grounding is effective only for unbalanced faults. Zero-sequence impedance comes into picture to restrict the fault current only in case of faults like line-generator to-ground or line-to-line-to-ground. Physically the resistance in the neural of the transformer represents absorption of electrical energy which, in turn reduces the accelerating energy and thus improves the transient stability [17][22]. The grounding resistor consumes power during a ground fault and thus exerts braking effect on the synchronous machine. Grounding located near a generator is, therefore, beneficial.

6. Turbine Fast Valving:

One reason for power system instability is the excess energy supplied by the turbine during the disturbance period. Fast valving is a means of reducing turbine mechanical input power due to a transmission system fault. This can be initiated by load impedance relays, acceleration transducers or by relays that recognize only severe transmission system faults. For maximum stability gains with fast valving the turbine input power should be reduced as fast as possible. During a fast valving operation, the interceptor valves are rapidly shut (in 0.1 to 0.2) second and immediately re-opened.

Presently some stations in USA have been put to use fast valving schemes.

7. Application of braking resistors:

An alternative means for fast turbine valving action is application of braking resistors. Braking resistors is the concept of applying an artificial electric load to correct a temporary imbalance between power generated and power delivered. During a fault the resistors are connected to the terminals of the generator through circuit breakers by means of controlling scheme. The control scheme determines the amount of resistance to be connected and its duration. The braking resistors remain on for a matter of cycles both during fault clearing and after system are restored to normal operation. A few cycles after the clearance of faults the same control scheme disconnects the braking resistor [22].

8. Single pole switching

Single pole switching or independent pole operation of circuit breaker refers to the mechanism with which the three phases of the breaker are closed and opened independently of each other. The failure of any one of the phase does not automatically prevent any of two remaining phase from proper operation. However for a 3-phase fault the three phases are simultaneously activated for operation by the same relaying scheme. The three phases are mechanically independent such; that the mechanical failure of any one pole is not propagated for the remaining pole.

Single pole switching is used at location where the design criterion is to guard against a three-phase fault compounded with breaker failure [18][23]. The successful independent pole operation of the filed breaker will reduce a three-phase fault to a single L-G fault (if one pole of the breaker is stuck), or to L-L-G fault (if two poles of the breaker are stuck). This criterion can be applied to the substation of a generating plant with multiple transmission outlets.

The advantages of single poles switching they are among the cheapest stability aids. Single pole switching operation is most efficient at high transmission voltages where equipment’s are costlier. Successful single pole switching may allow the critical clearing time of a plant circuit breaker to increase by, as much as; 2 to 5 cycles [8].

Most EHV circuit breakers are equipped with separate pole mechanism due to the large component size and wide phase space requirements at high working voltages. This method is very complex because it needs to provide separate trip coils to activate each pole [3].

9. Use of Quick-Acting Automatic Voltage Regulators:

The satisfactory operation of synchronous generators of a complex power system at high power (or load) angles and during transient condition is very much dependent on the source of excitation for the generators and the automatic voltage regulator. The power output of a generator is proportional to internal voltage E. Under fault conditions the terminal voltage falls.

A quick-acting voltage regulator causes to increase in E so that the terminal voltage remains constant. A higher value of E means a higher generator output. It has already been shown that the maximum value of a power angle curve is proportional to the per unit excitation. Field forcing can therefore, cause the machine to operate on a higher power-angle curve thereby allowing it to swing through a larger angle from its original position before it reaches the critical clearing angle[5][13].

2.9 FACTS Devices Technology Development

The technology behind thyristor-based FACTS controllers has been present for several decades and is therefore considered mature. More utilities are likely to adopt this technology in the future as more fast emerging GTO-based FACTS technology. Recent advances in silicon power-switching devices that significantly increase their power ratings will contribute even further to the growth of FACTS technology [4]. A relatively new device called the Insulated Gate Bipolar Transistor (IGBT) has been developed with small gate consumption and small turn-on and turn-off times. The IGBT has bi-directional current carrying capabilities.

More effective use of pulse width modulation techniques for control of output magnitude and harmonic distortion can be achieved by increasing the switching frequencies to the low kHz range. However, IGBT has recently been restricted to voltages and currents in the medium power range. The Integrated Gate Commutated thyristor (IGCT) combines the excellent forward characteristics of the thyristor and the switching performance of a bipolar transistor. In addition, IGCT does not require snubber circuits and it has better turn-off characteristics, lower conducting and switching loss, and simpler gate control compared with GTO and IGBT [7]. The ratings of IGCT reach 5.5 kV/1.8 kA for reverse conducting IGCTs and 4.5 kV/4 kA for asymmetrical IGCTs. Currently, typical ratings of IGCTs on the market are 5.5 kV/2.3 kA (ABB) and 6 kV/6 kA (Mitsubishi) [21].

Injection Enhanced Gate Transistor (IEGT) is a newly developed MOS device that does not require snubber circuits and it has smaller gate power and higher turn-on and turn-off capacity compared with GTO. The ratings of IEGT are in the order of 4.5 kV/1.5 kA.

Based on integration of the GTO and the power MOSFET, the Emitter Turn-Off (ETO) thyristor is presented as a promising semiconductor device for high switching frequency and high power operation. The ETO has 5 kA snubberless turn off capability and much faster switching speed than that of GTO. A modular ETO-based 1.5MVA H-bridge converter is used to build a cascaded-multilevel converter for high power FACTS devices [3][4].

A novel approach to distributed FACTS controllers based on active variable inductance has been recently proposed to realize cost-effective power flow control [6]. The power flow control using distributed FACTS controllers can be achieved by introducing a distributed series impedance concept which can be further extended to realize a distributed static series compensator.

2.9.1 Benefits of utilizing TCSC devices

The benefits of utilizing TCSC devices in electrical transmission systems can be summarized as follows:

- Elimination of sub synchronous resonance (SSR),
- Minimizing system losses,
- Improve power transfer capability
- Increase transmission system reliability and security.
- Improve dynamic and transient stability of power transmission systems,
- Increase quality of supply for sensitive industries.
- Improve voltage regulation and reactive power balance,
- Increased dynamic stability and Dynamic power flow control,
- Remove of damping of active power oscillations,

Generally Thyristor is a powerful tool for efficient power transmission and distribution system by changing impedance of the transmission line and controlling the inductive reactance of inductors connected in parallel to the capacitor. The magnitude of inductive reactance is determined by angle switching thyristors(α), which can also be Controlled by continuously flowing amplitude of current reactor from the maximum value to zero[6]. Angle switching thyristors can change inductive reactance controlled from a minimum value (α=0, $X_{tcr} = X_L$) theoretically to infinity (α=л/2;$X_{tcsc} = \infty$)

$$X_{tcsc} = \frac{X_c * X_{tcr}(\alpha)}{X_c - X_{tcr}(\alpha)} \tag{2.27}$$

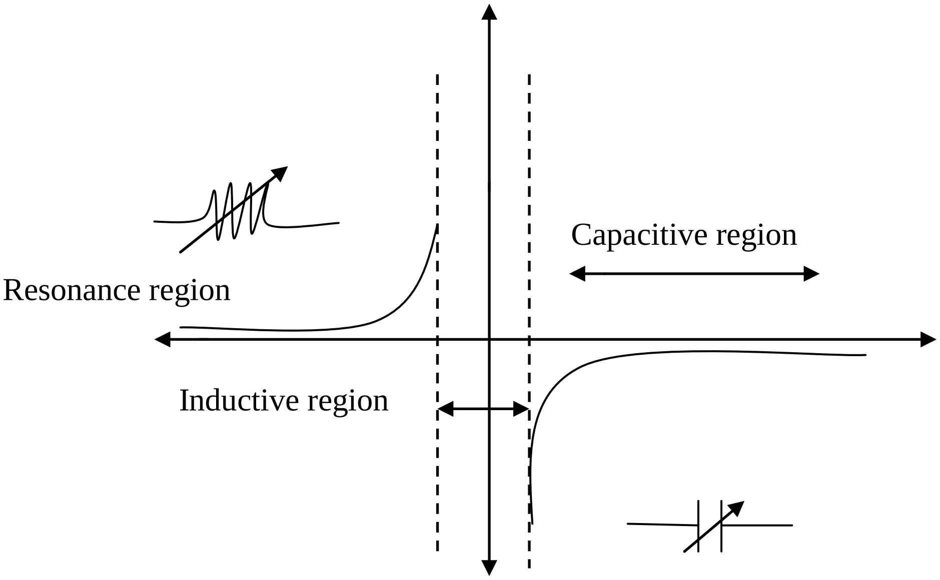


Fig.2. 5: Operational Regions of TCSC[23]

As per the TCSC characteristics, in inductive region the firing angle is 0-49deg and the reference impedance (19-80) ohm, and in capacitive region the firing angle (α) is 69-90degand the reference impedance (120-138) ohm. The TCSC can operate in both modes. However Inductive mode is rarely used in practice [7]

CHAPTER THREE
POWER SYSTEM DESIGN AND ANALYSIS

3.1 Introduction

The power system design and analysis are very important to ensure the maximum security of supplies with operational flexibility at an acceptable cost. In the development of the power system design a number of problems are identified, related to the constraints of fault levels and voltage regulation on the power systems due to large loads are discussed and analyzed. Alternative solutions are examined, and reasons are given for the solution adopted. One of the importance's of modeling the power system is for the solution of power systems problems, comparison of the previous model with the new modeling for flexible, reliable and secured operation of the power system. Let's consider single machine connected to infinite bus

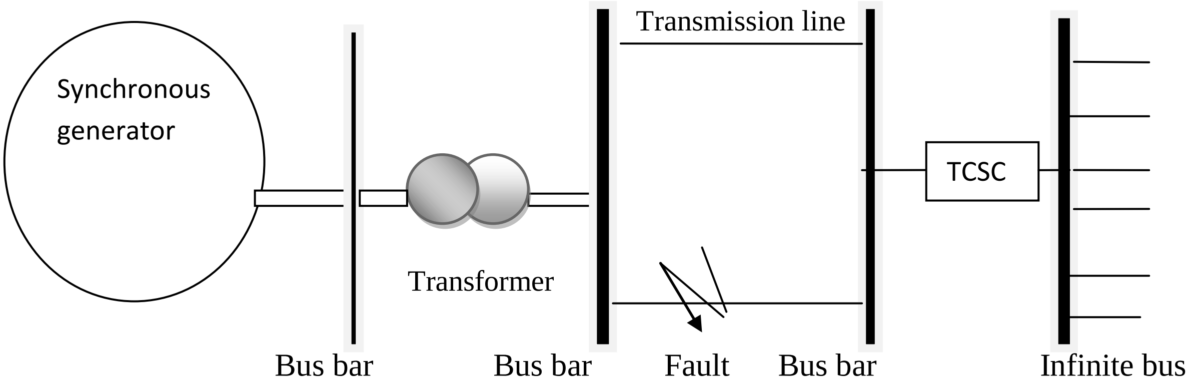


Fig.3. 1: Single machine connected to infinite bus with TCSC [24]

The synchronous generator is delivering power to the infinite-bus through a transmission line. As shown in fig 3.1. The following assumptions are used for a system of one machine connected to an infinite Bus. Often this assumption is valid for a multi-machine system.

- Mechanical input to generator remain constant
- Mechanical damping and AVR action are neglected
- The mechanical rotor angle of a machine coincides with the angle of the voltage behind the transient reactance.
- Loads are represented as a constant impedance/Admittance
- The mechanical angle of each machine coincides with electrical phase of voltage behind transient reactance

For the purpose of design and getting the targeted results, the following date shown in Table 3.1is used.

Table 3.1: The different devices parameter of gilgel gibe I is summarized below

No	Generator data		
1	Phase to phase rms voltage	13.8	KV
2	Frequency	50	Hz
3	Pf	0.9	
4	Nominal speed	428.6	Rev/min
5	Field current	3054.1	A
6	Maximum Speed	722	Rev/min
7	Excitation current	1030	A
8	Excitation voltage	144	V
The Autotransformer data			
1	Nominal power	40	MVA
2	I secondary	75.31	A
3	Winding one Phase to phase rms voltage	230	KV
4	Winding two Phase to phase rms voltage	132	KV
5	Frequency	50	Hz
6	I primary	174.9	A
No	Transformer data		
1	Winding one Phase to phase rms voltage	13.8	KV
2	Winding two Phase to phase rms voltage	230	KV
3	Total mass one Transformer	$106.5*10^4$	Kg
4	Oil (L)	28655	L
5	rising oil T^o	60	^0C
6	Core insulation T^o	65	^0C
7	I output (secondary)	179.35	A
8	I input (primary)	3054	A

3.2 The mathematical design of swing equation

When a major disturbance occurs, an imbalance is created between the generator and the load. The power balance at each generating unit (mechanical input power–electrical output power) differs from generator to generator. As a result, the rotor angles of the machines accelerate or decelerate beyond the synchronous speed for time greater than zero (t > 0). This phenomenon is called the “swinging” of the machines. There are two possible scenarios when the rotor angles are plotted as a function of time:

- The rotor angle increases together and the machine swings in unison (coherent) and eventually settles at new angles. As the relative rotor angles do not increases, the system is stable and in synchronism.
- One or more of the machine angles accelerates faster than the rest of the others. The relative rotor angle diverges as time increase. This condition is considered unstable or losing synchronism.

The swing equation states that the net torque, which causes acceleration or deceleration of the rotor of the synchronous generator, is the difference between the electromagnetic torque and mechanical torque applied to the generator [5]. What we need to understand is that event like faults, change of loads, switching operations and generation loss can lead to a disturbance in synchronism of the generator. Loss of synchronism means the rotor will be out of synchronous with stator. Swing curve determine how fast the rotor angle will come back to equilibrium after disturbance.

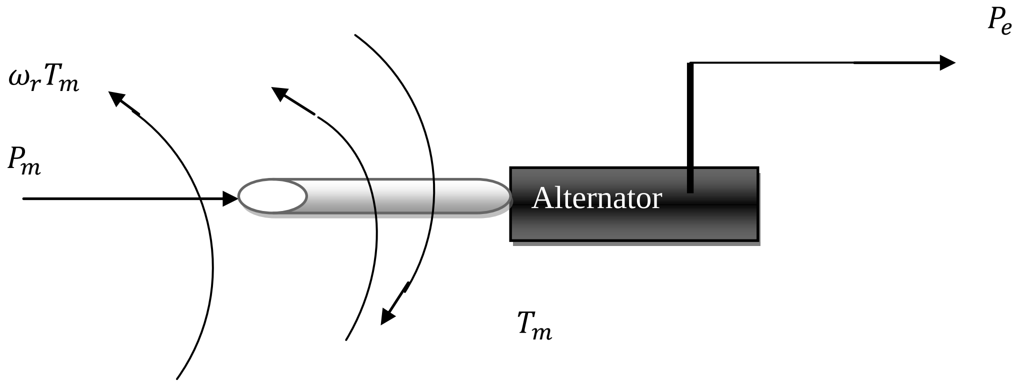


Fig.3. 2: Flow of power in a synchronous generator

Consider a synchronous generator developing an electromagnetic torque(T_e) and a corresponding electromagnetic power (P_e) while operating at the synchronous speed(ω_s). If the input torque provided by the prime mover at the generator shaft is T_m, then under steady state conditions (i.e. without any disturbance) the net torque causing acceleration is zero.

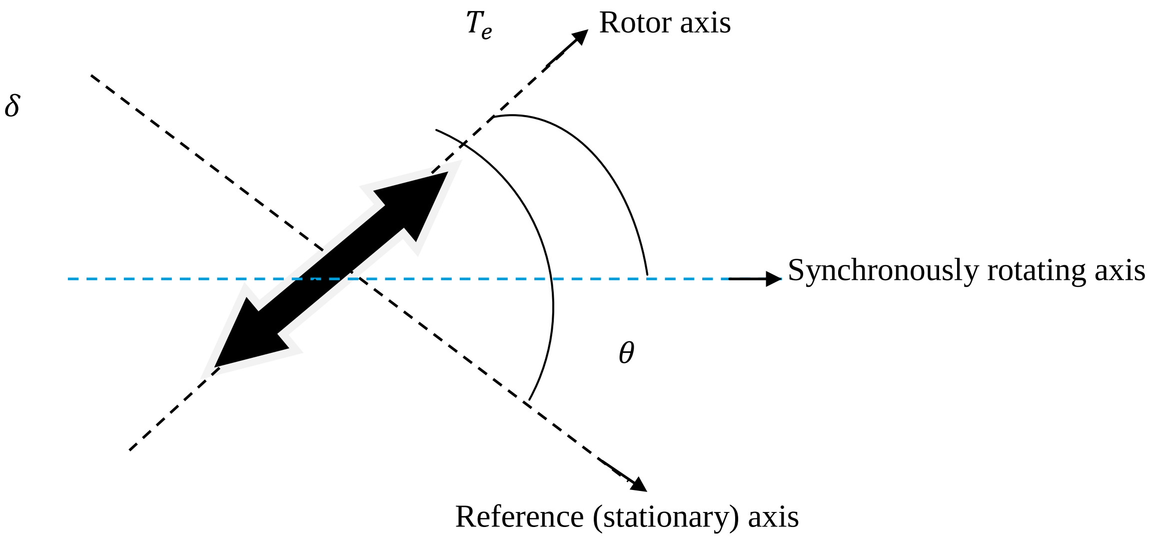


Fig.3. 3: Angular Position of rotor with respect to reference axis

When there is an imbalance between the torques acting on the rotor and the electrical torque then, the net torque causing acceleration or deceleration is given by [5]

$$T_a = T_m - T_e \tag{3.1}$$

Where,

T_a= accelerating torque in N.m

T_m= mechanical torque in N.m

T_e= electromagnetic torque in N.m

$T_a = T_m - T_e$ For generator

$T_a = T_e - T_m$ For Motor

If Tm is the driving mechanical torque and Te is the electrical torque then under steady state operation with friction and windage torques are neglected (because they are small in amount).

The two opposing torques are equal $T_m = T_e$,Under normal condition the relative position of rotor axis and resulting magnetic field axis is fixed. That is

$$T_m = T_e,\ Ta = 0 \tag{3.2}$$

During any disturbance the rotor may accelerate/decelerate with respect to synchronously rotating machine. Hence $T_m, T_e, T_a \neq 0$

$$T_a = T_m - T_e \tag{3.3}$$

Multiplying both side by ω_r

$$T_a\omega_r = T_m\omega_r - T_e\omega_r \tag{3.4}$$

The net accelerating power is

$$P_a = P_m - P_e \tag{3.5}$$

$$P_a\omega_r = T_a\omega_r = I\alpha\omega_r = \quad M^*\alpha = J\varepsilon\omega \tag{3.6}$$

Where, J – moment of inertia (kg-m^2); ε - angular acceleration (rad/sec^2); $M = I\omega_r$

Neglecting the losses, the difference between the mechanical and electrical torque gives the net accelerating torque Ta. In the steady state the electrical torque is equal to the mechanical torque and hence, the accelerating power will be zero. During this period the rotor will move at synchronous speed in $\omega_S$rad/s. The angular position θ is measured with a stationary reference frame. To represent it with respect to synchronously rotating frame, we define from fig (3.3)

$$\theta = \omega_s t + \delta \tag{3.7}$$

Where δ is the angular position in rad with respect to the synchronously rotating reference frame taking the time derivative of the above equation we get the equation shown below.

$$d\delta/dt = \omega_s + d\delta/dt = \omega_r \tag{3.8}$$

$$\frac{d^2\delta}{dt^2} = \frac{d^2\theta}{dt^2} = \frac{d\omega_r}{dt} = \alpha \tag{3.9}$$

Substitute equation (3.9) in to equation (3.6) and

$$P_a = \frac{Md^2\delta}{dt^2} = \frac{Md^2\theta}{dt^2} = P_m - P_e \qquad (3.10)$$

This is called **swing equation**

In stability studies H-constant called the per-unit inertia constant, is more frequently used by the manufacturers. Transient stability can be improved either by using machine of higher inertia or by connecting the synchronous motor to heavy flywheels. The inertia constant of the machine therefore given

$$H = \frac{\text{stored energy in magajoules}}{\text{Rating in MVA}} \qquad (3.11)$$

$$H = \frac{\frac{1}{2}J\omega_S^2}{S_{mech}} = \frac{\frac{1}{2}M\omega_S}{S_{mech}} \qquad (3.12)$$

$$M = \frac{2H}{\omega_S}S_{mech} = \frac{HS_{mech}}{\pi f} \qquad (3.13)$$

$$M = \frac{HS_{mech}}{180f} \qquad (3.14)$$

By subsisting in equation (3.14) in to equation (3.10) for the M values, now the swing equation becomes

$$\frac{H}{\pi f}\frac{d^2\delta}{dt^2} = P_a = P_s - P_e \qquad (3.15)$$

Where, P_m, P_e and P_a respectively are the mechanical, electrical and accelerating power in MW. We can therefore conclude that the rotor angular speed is equal to the synchronous speed only when $\frac{d\delta}{dt}$ is equal to zero.

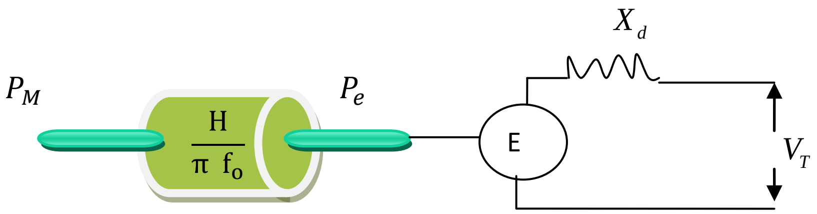


Fig.3. 4: The synchronous generator connected to infinite bus [3]

To have equivalent H for many machines:

$$H_e = H_1 \frac{S_1}{S_b} + H_2 \frac{S_2}{S_b} + \dots H_{(n)} \frac{S_n}{S_b} \tag{3.16}$$

H of the machine varies from 1 to 10sof seconds depending on the type and size of the machine

Table 3.2: The inertia constant for different types of machine

Type of the machine	Inertia constant [MJ/MVA]
Steam Turbine generator	3-10
Hydro generators	2-4
Synchronous motors	2
Induction motors	0.5
Synchronous condenser (reactive power generator)	1-1.25

Large H means, the machine is large and small H means the machine is small. In steam turbine since the generator is connected with several stages of turbines it takes much time inertia constant (H)

The angle between rotor axis and field axis is called power angle/torque angle (δ). The angle δ is the angle of the internal emf of the generator and it dictates the amount of power that can be transferred.

$$\delta = \frac{1}{M} \iint (P_m - P_e) \tag{3.17}$$

As shown in the fig (3.5) in unstable system δ increases indefinitely with time and machine loss synchronism. Whereas; in the stable system δ under goes oscillation which eventually die out due to damping of the machine. From the fig 3.5 for a system to be stable the first derivative at any where is zero $(\frac{d\delta}{dt} = 0)$

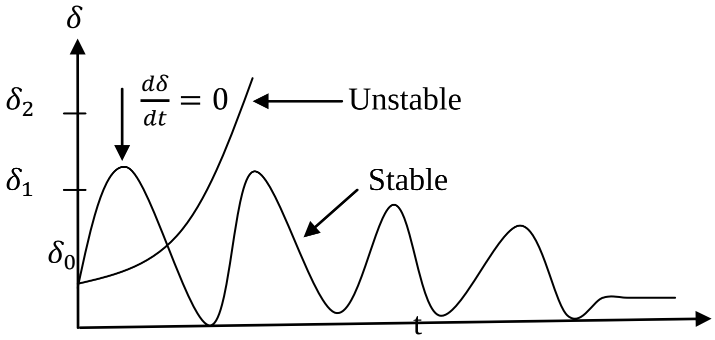


Fig.3. 5: Plot of δ verses time for a stable and unstable system [8]

3.3 Series Compensation

The control scheme of shunt device is effective in maintaining the overall effect of voltage profile of the transmission line. However it is ineffective in controlling the overall transmitted power which ultimately depends upon the impedance of the transmission line and the angle between end line voltages. The main idea of series compensation is to decrease the overall transmission line impedance as can be seen from the diagram below

Power transfer

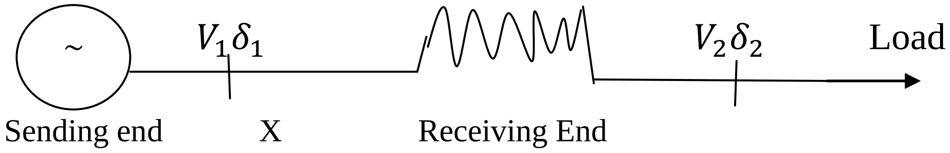


Fig.3. 6: Single machine connected to the load

$$P_m=(\frac{V_1V_2)}{X}\ \sin(\delta_1-\delta_2) \tag{3.18}$$

Overall effective Impedance is reduced by inserting capacitor in series with transmission Line. Compensating capacitor is connected in series which cancels a portion of actual line Reactance. There by The effective transmission impedance is reduced by

$$X_{eff}=X-X_c \tag{3.19}$$

Where, $X_c = kX$ for 0<k<1

$$X_{eff}=(1-K)X \tag{3.20}$$

The effect of series compensation by this active and reactive power can be seen in the equation below.

Current in the compensated line is

$$I=\frac{2V}{(1-k)X}\ \sin(\delta/2) \tag{3.21}$$

Real power transmitted

$$P=\frac{V^2}{(1-k)X}\sin\delta \tag{3.22}$$

Reactive power supplied by the series capacitor

$$Q=\frac{2V^2}{X}\ \frac{k}{(1-k)^2}\ (1-\cos\delta) \tag{3.23}$$

The transmittable power rapidly increases with the degree of series compensation (k) and the reactive power supplied by the capacitor also increase with the degree of k. So, Series capacitor having been extensively used in the last fifteen years thought the world for the compensation of long transmission line

3.4 Thyristor Controlled Series Compensator (TCSC)

TCSC is a capacitive reactance compensator which consists of a series capacitor bank shunted by a thyristor controlled reactor in order to provide a smoothly variable series reactance. TCSC can control the line impedance through the introduction of a thyristor controlled capacitor in series with the transmission line.

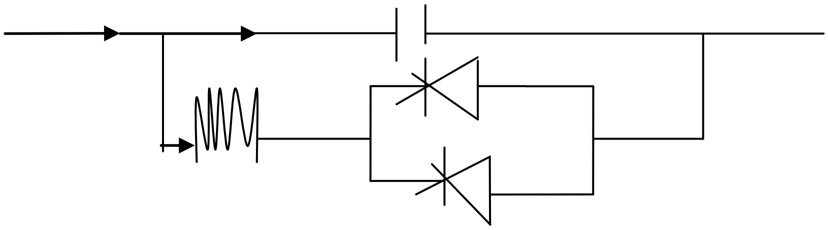


Fig.3. 7: TCSC circuit block diagram

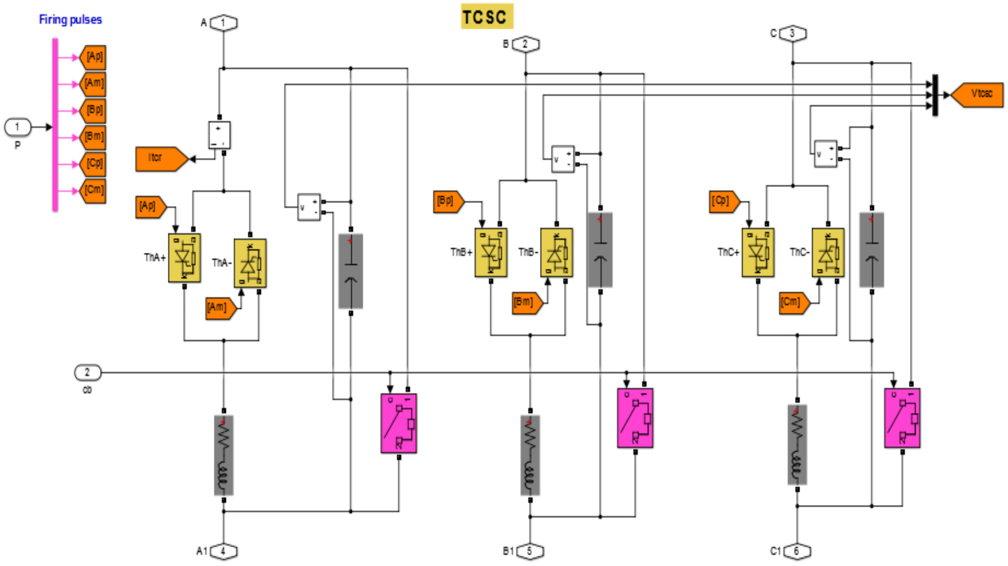


Fig.3. 8: The internal structure of TCSC

The overall working principle of the TCSC is based on the following principles

$$Z_{eq} = (-j\frac{1}{\omega C} // (j\omega L) = -j\frac{1}{(\omega C - 1/\omega L)} \qquad (3.24)$$

That is if

1. $\omega\mathrm{C}-\dfrac{1}{\omega\mathrm{L}}>0$, the reactance of the fixed capacitor is less than that of the parallel connected variable reactor and this combination provides a variable capacitive reactance.
2. $\omega\mathrm{C}-\dfrac{1}{\omega\mathrm{L}}=0$, A resonance develops that result in infinite capacitive impedance, and this is an unacceptable condition
3. $\omega\mathrm{C}-\dfrac{1}{\omega\mathrm{L}}<0$, the combination provides a variable inductive reactance. This situation

corresponds to the inductive mode of operation. Normally TCSC operate under capacitive mode

3.4.1 Design of the TCSC

A TCSC is a parallel combination of TCR and a fixed capacitor. The TCR reactance as a function of firing angle is given by [2]

$$\mathrm{X}_{\mathrm{L}\,(\alpha)}=\mathrm{X}_{\mathrm{L}}\,\frac{\pi}{\pi\text{-}\alpha\text{-}\sin 2\alpha} \tag{3.25}$$

As the variable reactance comes in parallel with the fixed capacitor in the equivalent circuit, the capacitance can be considered to be variable as well [24].

$\mathrm{X}_{\mathrm{L}}=2\pi fL$, and the steady state fundamental reactance of the TCSC is given by [3]

$$\mathrm{X}_{TCSC}=\frac{\mathrm{X}_{C}*\mathrm{X}_{L(\alpha)}}{\mathrm{X}_{C}\text{-}\mathrm{X}_{L(\alpha)}} \tag{3.26}$$

Therefore by varying the conduction angle inductive reactance of the fundamental reactance of the TCSC can be controlled and can be made either inductive or capacitive. Putting the value of $\mathrm{X}_{L(\alpha)}$ in the above relation (3.26), the following result equation (3.27) is obtained

$$\mathrm{X}_{TCSC(\alpha)}=\text{-}\mathrm{X}_{C}+C_{1}(2(\pi-\alpha))+\sin(2(\pi-\alpha))-C_{2}\cos^{2}(\pi-\alpha)\varpi\tan(\varpi((\pi-\alpha))-\tan(\pi-\alpha)) \tag{3.27}$$

Where $\mathrm{X}_{\mathrm{LC}}=\dfrac{X_{C}X_{L}}{X_{C}-X_{L}}$, $\mathrm{C}_{1}=\dfrac{X_{C}+X_{L}}{\pi}$ $\mathrm{C}_{3}=\dfrac{4X^{2}{}_{CL}+X_{L}}{\pi X_{L}}$ $and\ \varpi=\dfrac{\sqrt{X_{C}}}{X_{L}}$

3.5 Analysis of equal area criteria for transient stability

From swing equation; $\mathrm{M}\,\dfrac{\mathrm{d}^{2}\delta}{\mathrm{dt}^{2}}=\mathrm{P}_{\mathrm{m}}\text{-}\mathrm{P}_{\mathrm{e}}$ and multiplying both sides by $2\frac{d\delta}{dt}$

$$\mathrm{M}\,\frac{\mathrm{d}^{2}\delta}{\mathrm{dt}^{2}}2\frac{d\delta}{dt}=2\frac{\mathrm{d}\delta}{dt}(\mathrm{P}_{\mathrm{m}}\text{-}\mathrm{P}_{\mathrm{e}}) \tag{3.28}$$

$$\frac{d^2\delta}{dt^2}2\frac{d\delta}{dt}=2\frac{d}{dt}\left(\frac{d\delta}{dt}\right)^2 \tag{3.29}$$

$$M\frac{d}{dt}\left(\frac{d\delta}{dt}\right)^2=2\frac{d\delta}{dt}(P_m-P_e) \tag{3.30}$$

Integrating both sides of the above equation;

$$M\left(\frac{d\delta}{dt}\right)^2=2\int\frac{d\delta}{dt}(P_m-P_e) \tag{3.31}$$

$$\frac{d\delta}{dt}=\sqrt{\frac{2}{M}\int\frac{d\delta}{dt}(P_m-P_e)} \tag{3.32}$$

$\frac{d\delta}{dt}=\omega$ (Relative speed w. r. t synchronously rotating generator) thus for stable system $\frac{d\delta}{dt}=0$

Let us consider

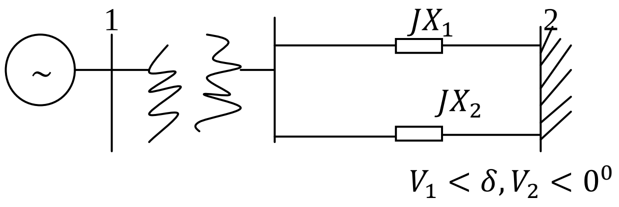


Fig.3. 9: The single machine tied to infinite bus with two parallel transmission lines [12]

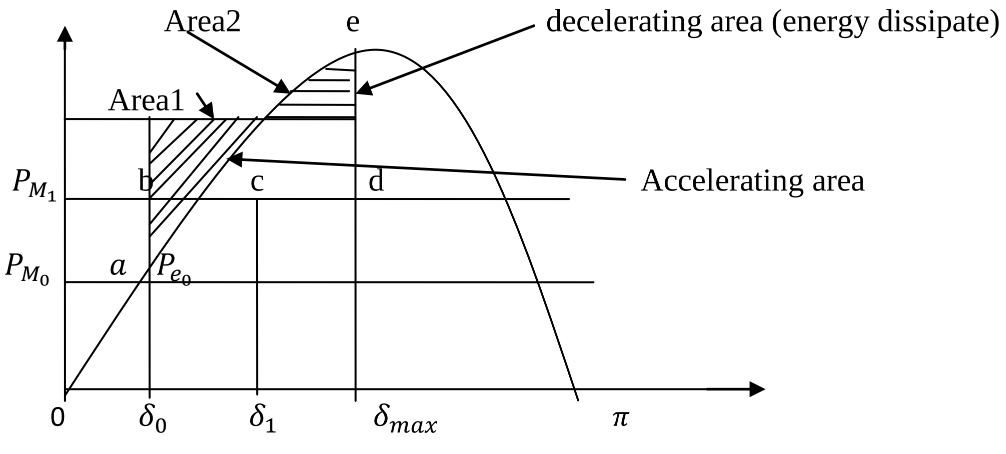


Fig.3. 10: Equal area criteria during sudden increase of P_m in power system

Initially the machine is operating at point a, (P_{mo} ,P_{eo}) which is steady state operation. During sudden increase of P_m, that is P_m>P_e

The machine will accelerate (rotate more than synchronous speed) energy will be stored in the form of KE as a result δ keep increasing until energy dissipate equal with energy stored (δmax) to decelerate. Post increments the system will operate at a point (a, e) that the machine will decelerate and energy dissipated. Finally rotor speed=synchronous speed but $P_e>P_m$. To maintain $P_e=P_m$, the machine will oscillate between point a- e. Due to the damping of the machine the oscillation settle around point c

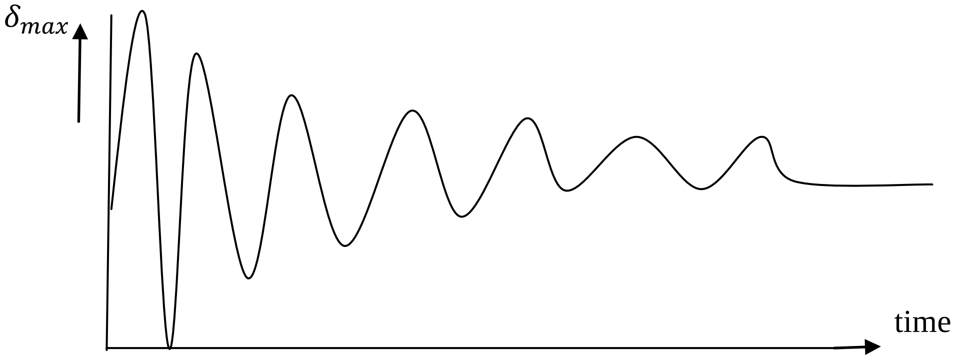


Fig.3. 11: Rotor angle verses time of the generator

3.5.1 Sudden loss of one of the parallel line

Let's consider single machine tied to infinite bus system

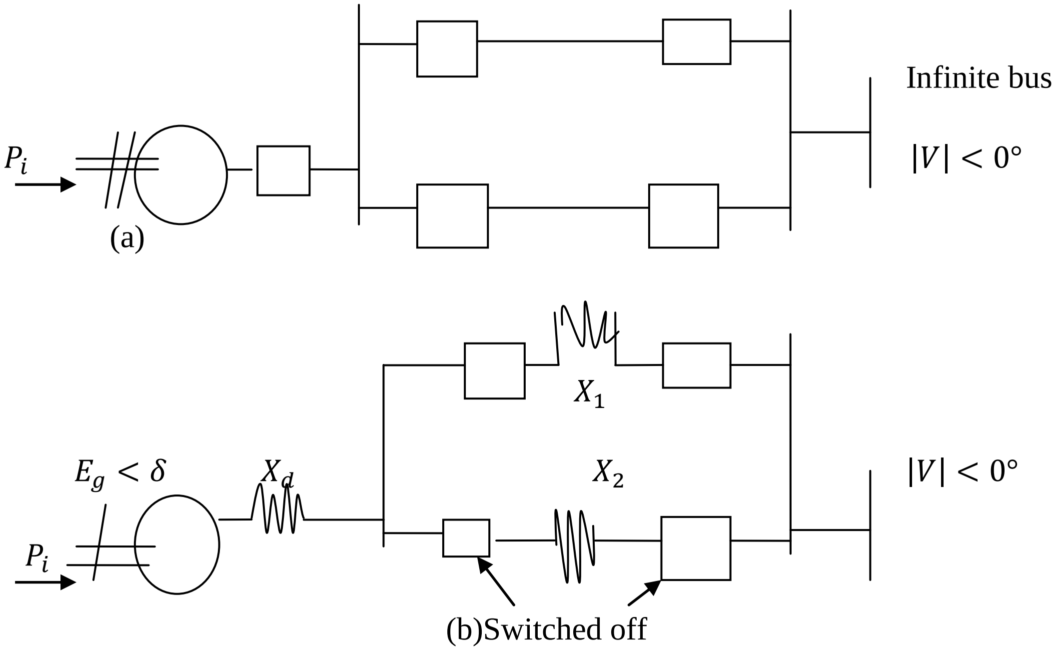


Fig.3. 12: Single machine tied to infinite bus through two parallel lines

Consider a single machine tied to infinite bus through parallel lines as shown in Fig. 3.12(a). The circuit model of the system is given in Fig. 3.12(b). Let‘s study the transient stability of the system when one of the lines is suddenly switched off and with the system operating at a steady load. Before switching off, power angle curve is given by

$$P_{eI} = \frac{|E_g||V|}{(X_d + X_1//X_2)} \sin\delta = P_{maxI} \sin\delta \tag{3.33}$$

Immediately on switching of Line 2 Power angle curve is given by

$$P_{eII} = \frac{|E_g||V|}{X_d + X_1} \sin\delta = P_{maxII} \sin\delta \tag{3.34}$$

Where,$P_{maxII} < P_{maxI}$since,$X_d + X_1 > X_d + X_1//X_2$ the system is operating initially with steady state power transfer $P_e = P_i$ at torque angle δ_0 on curve I.

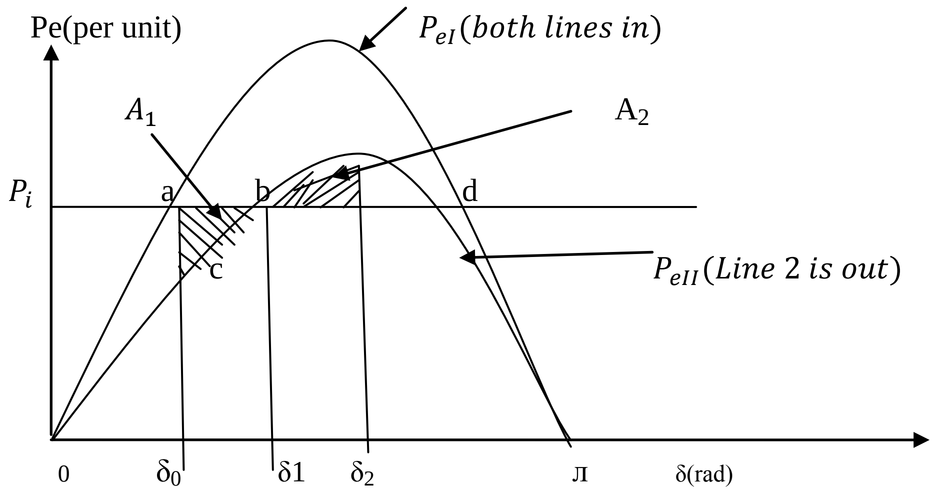


Fig.3. 13: Equal area criterion applied to the opening of one of the two lines in parallel

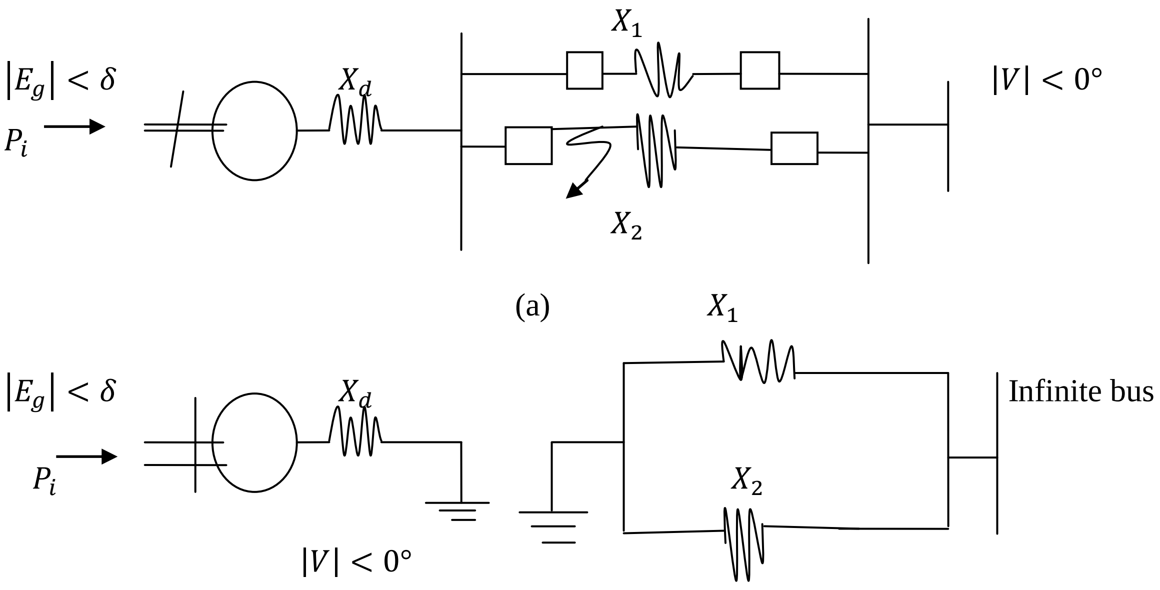
On switching off line2, the electrical operating point shifts to curve II (point b). Accelerating energy corresponding to area A_1 is put into rotor followed by decelerating energy for δ >δ1. Assuming that an area A_2 corresponding to decelerating energy (energy out of rotor) can be found in such a way that such that $A_1 = A_2$. The system will be stable and will finally operate at c corresponding to a new rotor angle which is needed to transfer the same steady power.

If the steady load is increased (line Pi is shifted upwards) a limit is finally reached beyond which decelerating area equal to A_1 cannot be found and therefore, the system behaves as an unstable one. For the limiting case, δ_1 has a maximum value given by

$$\delta_1=\delta_{max}=\pi-\delta_0 \tag{3.35}$$

3.5.2 Sudden Short Circuit on One of Parallel Lines

(1) Short circuit at one end of line:- Let us a temporary three phase bolted fault occurs at the sending end of one of the line.



(a)

(b)

Fig.3. 14: Short circuits at one of the line

Before the occurrence of a fault, the power angle curve is given by

$$P_{eI}=\frac{|E_g||V|}{X_d+X_1//X_2}\sin\delta=P_{maxI}\sin\delta \tag{3.36}$$

Upon occurrence of a three-phase fault at the generator end of line 2, generator gets isolated from the power system for the purpose of power flow as shown Fig. 3.14 (b). Thus during the period the fault lasts.

$$P_{eII}=0 \tag{3.37}$$

The rotor therefore accelerates and angles δ increases. Synchronism will be lost unless the fault is cleared in time. The circuit breakers at the two ends of the faulted line open at time t_c

(corresponding to angle δ_c). The power flow is now restored via the healthy line (through higher line reactance X_2 in place of ($X_1//X_2$), with power angle curve

$$P_{eIII} = \frac{|E_g||V|}{X_d + X_1}\sin\delta = P_{maxIII}\sin\delta \tag{3.38}$$

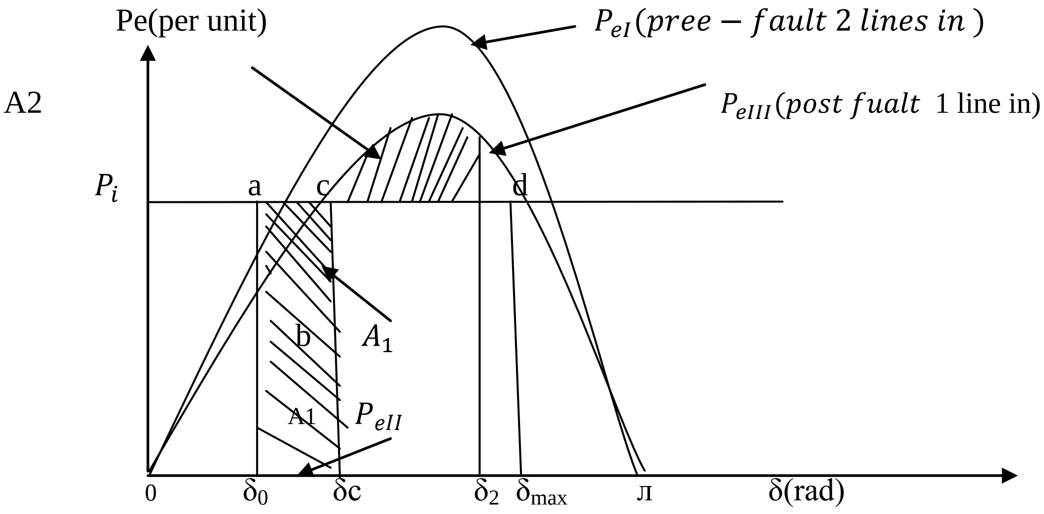
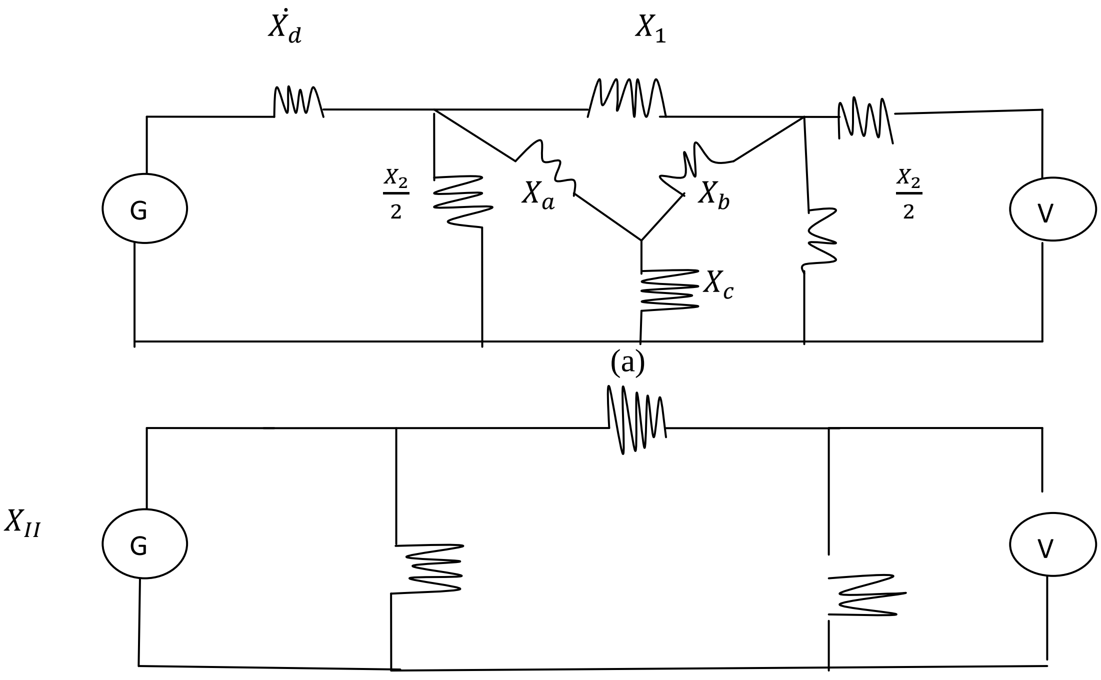


Fig.3. 15: Equal area criteria applied to the system

The rotor now starts to decelerate as shown in Fig 3.15 the system will be stable if a decelerating area A_2 can be found equal to accelerating area A_1 before δ reaches the maximum allowable valueδ_{max}. As area, A_1depends upon the clearing time t_c (corresponding to clearing angle δ_c), clearing time must be less than a certain value (critical clearing time) for the system to be stable.

(2**) Short circuit at the middle of a line**:-When the fault occur at the middle of a line or away from line ends, there is some power flow during the fault. Circuit model of the system during the fault is shown in fig. 3.16(a) and the circuit reduces to fig. 3.16(b) through one delta-star and star-delta conversion. The power angle curve during the fault is given by

$$P_{eII} = \frac{|E_g||V|}{X_d + X_1}\sin\delta = P_{maxII}\sin\delta \tag{3.39}$$



(a)

(b)

Fig.3. 16: Circuit model for short circuit at the middle of the line

P_{eI} and P_{eIII} As in and P_{eII} as obtained above are all plotted in Fig.3.17

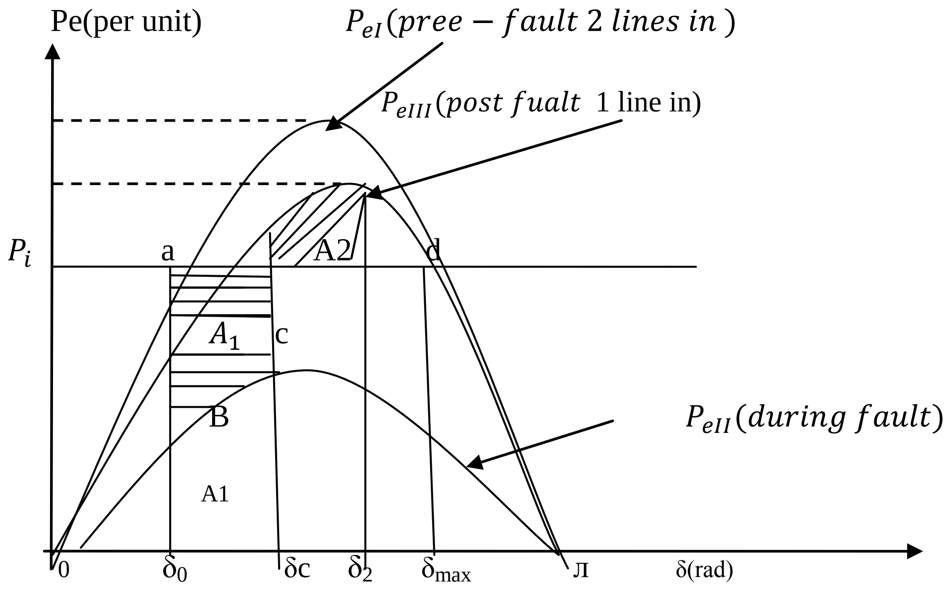


Fig.3. 17: Equal area criteria for fault on the middle of the system with $\delta_c < \boldsymbol{\delta_{cr}}$

Accelerating area (A_1) corresponding to a given clearing angle (δ) is less in this case. Stable system operation is shown in fig.3.17, where it is possible to find the area A_2 equal to A_1 for $\delta_2 < \delta_{max}$.

As the clearing angle δ_c is increased, area A1 increases and to find $A_2 = A_1$, δ_2 increases till it has a value δ_{max}, which is the maximum allowable value for stability. This is a case of critical clearing angle which is shown in Fig. 3.18.

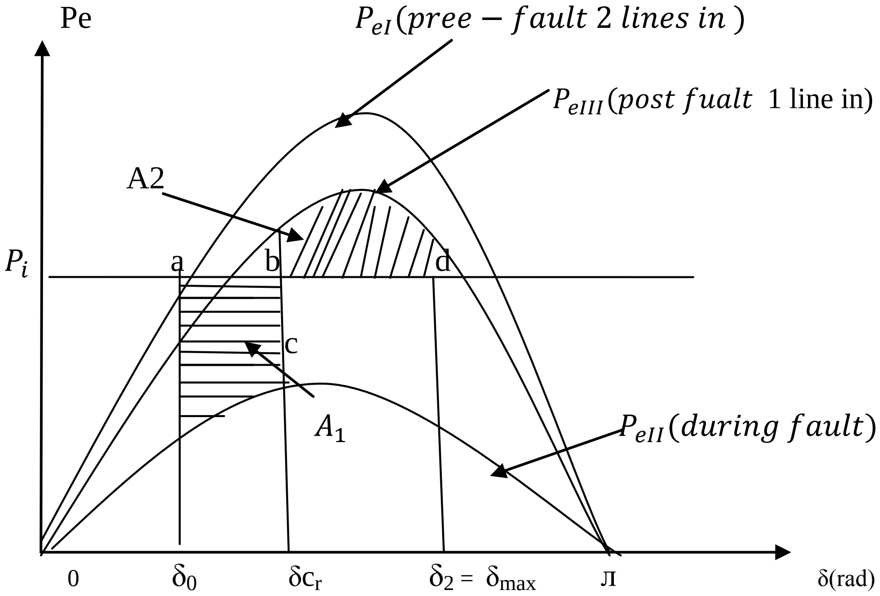


Fig.3. 18: Equal area criteria for fault on the middle of the system.

Applying equal area criteria to the case of critical clearing angle of fig.3.18 we can write

$$\int_{\delta o}^{\delta cr} (P_i - p_{\max II} \sin\delta) d\delta = \int_{\delta cr}^{\delta \max} (P_i - p_{\max II} \sin\delta) d\delta \tag{3.40}$$

Where,
$$\delta_{\max} = \pi\text{-}\sin^{-1}\frac{\mathrm{P_i}}{\mathrm{P_{maxII}}} \tag{3.41}$$

Integrating the above equation 3.40 we get

$$\delta_{\max} = \mathrm{P_i}(\delta_{cr} - \delta_o) + \mathrm{P_{maxII}}(\cos\delta_{cr} - \cos\delta_o) = 0 \tag{3.42}$$

$$\cos\delta_{cr} = \frac{\mathrm{P_i}(\delta_{\max} - \delta_o) - \mathrm{P_{maxII}}\cos\delta_o) P_{\max III}\cos\delta_o}{P_{\max III} - \mathrm{P_{maxII}}} \tag{3.43}$$

The critical clearing angle is in radian. The equation modifies as below if the angles are in degree

$$\cos\delta_{cr} = \frac{180}{\pi}\left[\frac{\mathrm{P_i}(\delta_{\max} - \delta_o) - \mathrm{P_{maxII}}\cos\delta_o) P_{\max III}\cos\delta_o}{P_{\max III} - \mathrm{P_{maxII}}}\right] \tag{3.44}$$

Stability margin: – is also one of an indicator of stability of the system. It is the difference between actual clearing time and critical clearing time

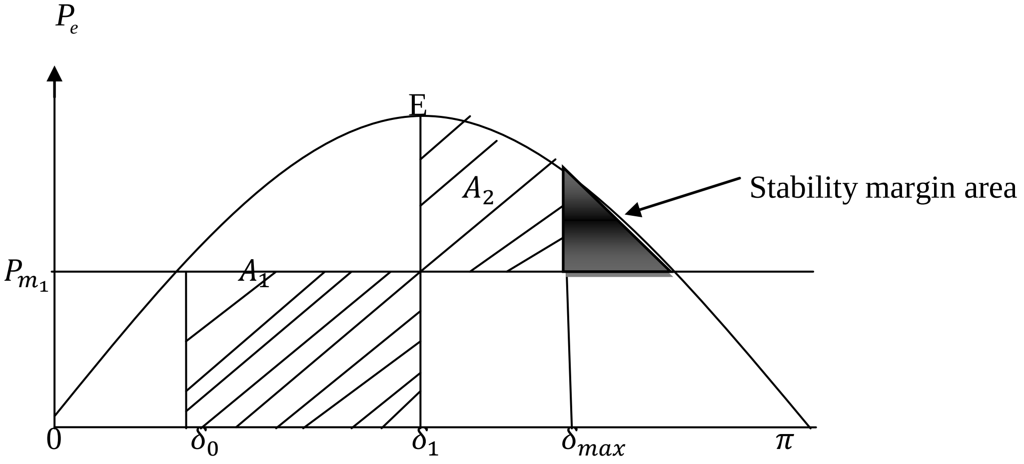


Fig.3. 19: Stability margin [17]

The larger the margin area the more stable system with zero margins will easily goes to disturbance.

Consider the power system in Fig (3.20) it is referred to as a one-machine against an infinite bus. Many engineers use it to provide conceptual basis for understanding fundamental machine behavior. Let's study and analyze the behavior of the machine numerically.

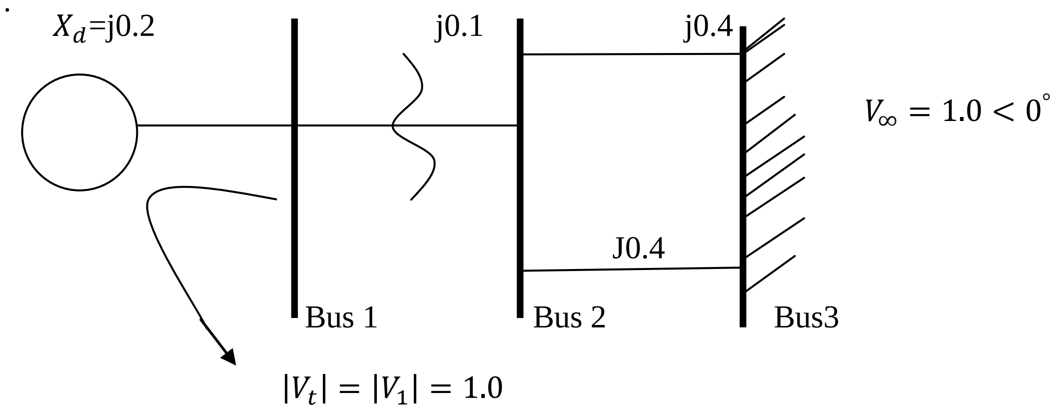


Fig.3. 20: Single machine connected to infinite bus

Bus 3, the infinite bus, is so-called because it has a voltage and angle that is constant under all conditions, and it can absorb infinite power.

Although there is no real infinite bus in power systems, a single small machine connected to a very large power system behaves as it is connected to an infinite bus. Assume that the machine is delivering 1.0 per unit power under steady-state conditions from which we can computes the current flow from every generator bus, and then each generator's internal voltage.

1. Determine the voltage at Generator Ea.
2. Draw the power-angle (P-δ) curve.
3. Determine the point corresponding to the 1.0 P.u power condition on the pre-fault power angle curve.
4. Consider the fault in the middle of one of the lines between buses 3 and 2, determine the fault-on power angle curve
5. Determine the post-fault or after fault power-angle curve after protection has operated to clear the fault.
6. Use the three curves to describe what happens to the angle δ during the three Periods i.e. in pre-fault, fault-on, and post-fault condition.

Case 1

Determine voltage at the generator Ea.

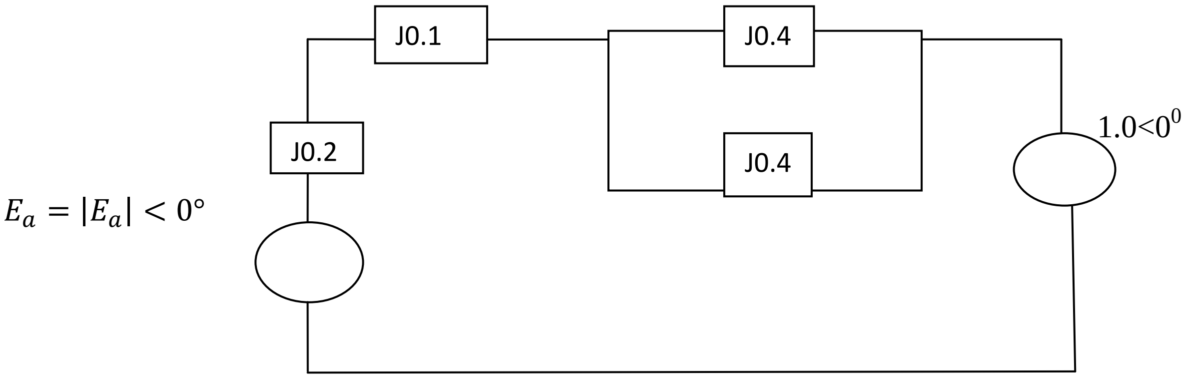


Fig.3. 21: The circuit model of single machine infinite bus

Computing the impedance x between the generator terminals and the infinite bus:

X=0.2+0.1+0.4//0.4=0.1+0.2+0.2=0.5

Since there is two bus having voltage magnitudes and reactance between them the power flowing at the Generator terminals before the fault happen is given by

$$P_{pre} = \frac{|V_1||V_\infty| \sin \delta_{1\infty}}{X} = \frac{(1)(1) \sin \delta 1_\infty}{0.5} = 2.0 \sin \delta 1_\infty = 1.0$$

$$\delta 1_{\infty}=30.0^0 \text{ and } V_1=1<30.\ 0^0$$

From this value the current flowing from the machine terminals (bus 1) to the infinite bus, can be determined according to the voltage current relation.

$$I=(1< 30.0\ ^0 - 1<0^0)\frac{1}{j0.5}=0.5172< 75\ ^0$$

The internal voltage E_a computed according to

$$E_a = V_1 + I(j0.2)$$

$$=1<30.0\ ^0+0.517<75^0*(j0.2)$$

$$=1.5<24^0$$

The above procedure is typical of what is done in full-scale commercial power flow programs where the program will begin from a power flow solution, from which it computes the current flow from every gen bus, and then it computes each generator's internal voltage.

The power power-angle curve (P-δ) for different cases is drowning that has been explained so far for different angles shown below.

$$P_{pre}=\frac{|V_1||V\infty|\ \sin\delta 1\infty}{X}$$

Note that the electrical power (left-hand-side) is the same in all three cases since there is no resistance in this circuit. We should choose the most restrictive power angle curve, i.e. the one that gives the largest angle for the same power. Since the voltages are all reasonably close, the most restrictive curve is determined by the one with the largest reactance

By using the above numerical data to find the pre fault power pre

$$P_{pre}=\frac{|E_a|\ |V\infty|\ \sin\delta a\infty}{0.5}=2.0\sin\delta a\infty=1.0$$

The operation point corresponding to the 1.0 p.u power condition on the pre-fault power angle curve is where P_e =1.0 and Solving for δ_a =30.0°. On the pre-fault power-angle curve however, that there are really two solutions, one at 30.0° and the other at 180-30.0°=150.0° both of these points constitute equilibrium. Since, the two angles are complementary.

Case 2

Consider the three phase fault in the middle of one of the lines between buses 3 and 2inorder to determine the power angle curve the equivalent reactance is determined. From the equivalent circuit diagram corresponding to the faulted system is.

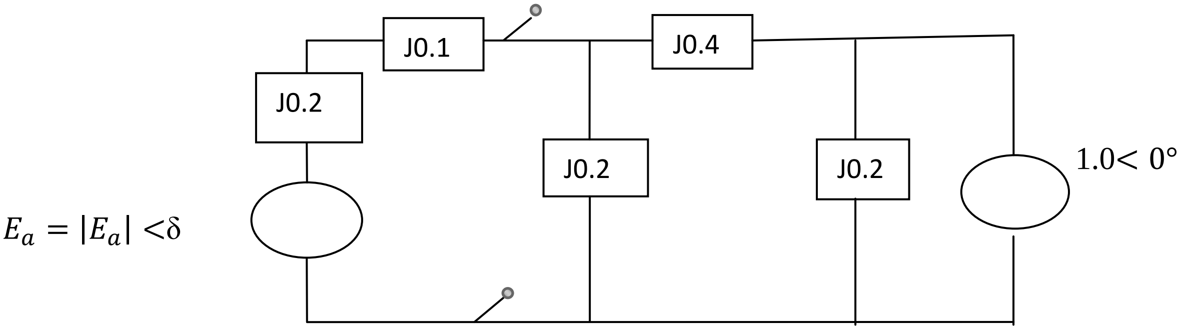
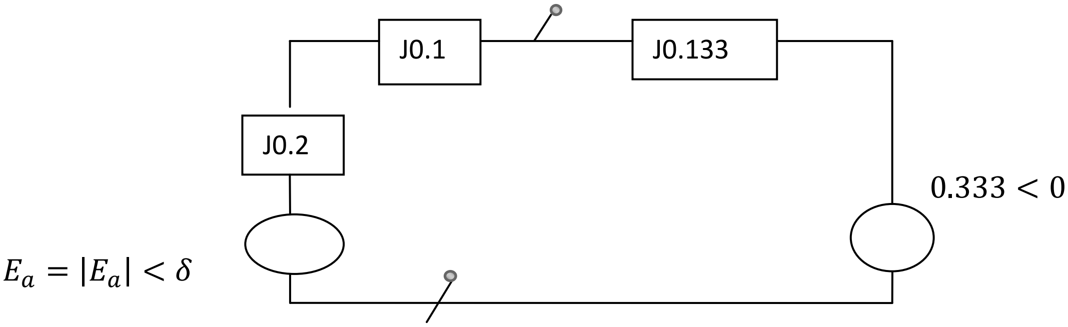


Fig.3. 22: Circuit models for fault in the middle of one of the line

So we want to write another equation in this condition. To write such equation, however, the series reactance is needed between the two voltage sources. This series reactance is not obvious that we can get from the circuit diagram. The relevant part of the circuit is shown below

$$V_{thev} = 1.0 < 0° \frac{0.2}{0.2+0.4} = 0.3333 < 0°$$



$$Xa_{thev} = 0.2 + 0.1 + 0.1333 = 0.4333$$

Then power-angle equation will be

$$p_{fault} = \frac{|E_a||V_\infty| \sin \delta athev}{Xathev} = \frac{(1.05)(0.33) \sin \delta athev}{0.4333} = 0.8077$$

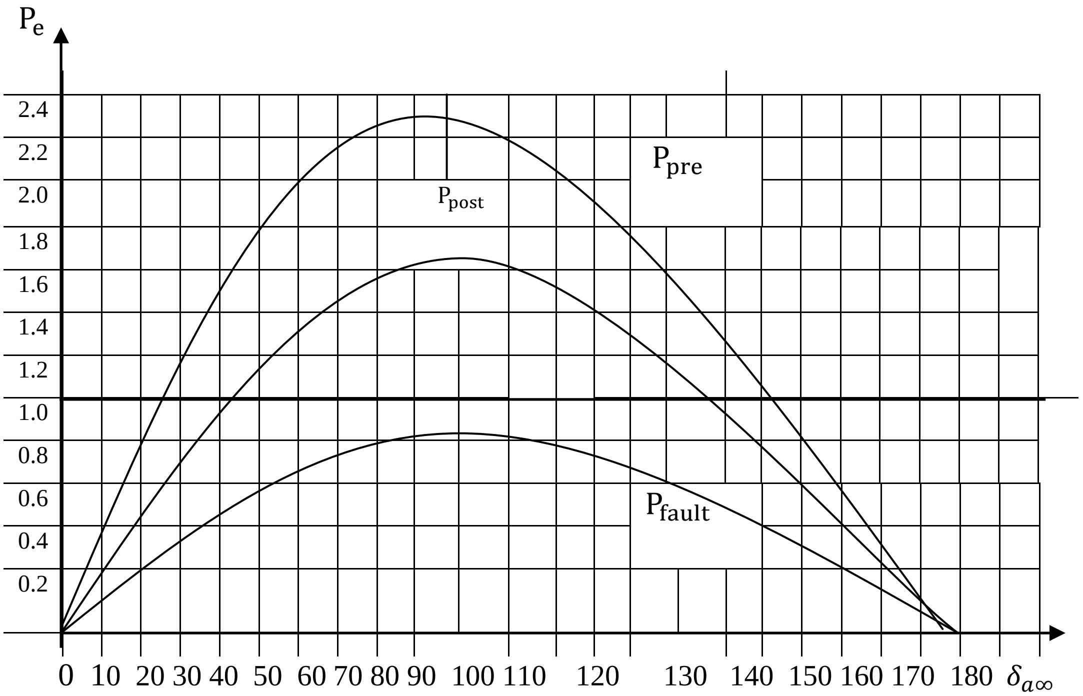


Fig.3. 23: Power angle curves for pre fault and post fault condition

Case 3

To determine the post-fault power-angle curve after protection has operated to clear the fault. The post-fault system is obtained from the understanding of basic protective relaying which results in removing the faulted circuit. The resulting one-line diagram is shown, and the corresponding equivalent circuit diagram is

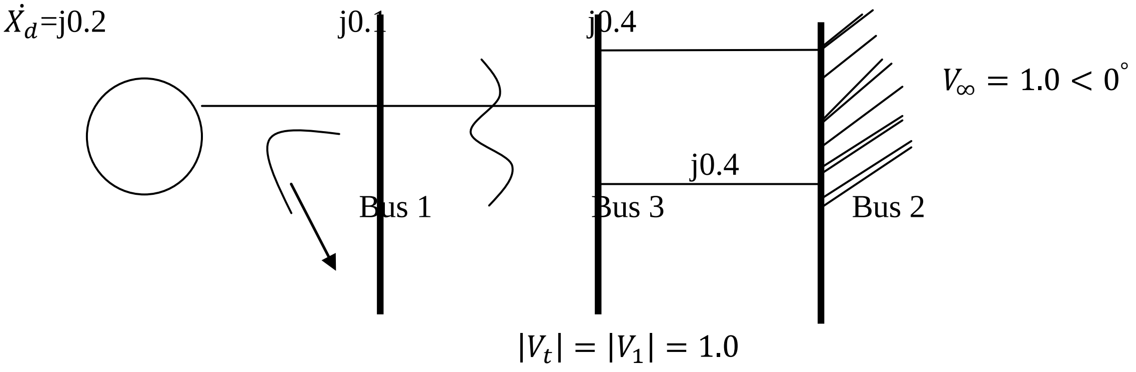


Fig.3. 24: Single machine connected to infinite bus after fault is removed

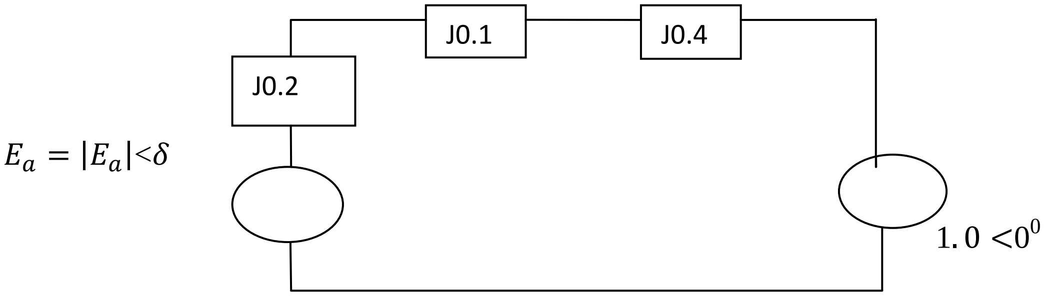


Fig.3. 25: Circuit diagram of single line after fault is removed

$$P_{post} = \frac{|E_a||V_\infty| \sin \delta a \infty}{X} = \frac{(1.05)(1.0) \sin \delta a \infty}{0.7} = 1.5 \sin \delta a\ \infty$$

On the post-fault power angle curve this is where P_e=1.0,

$$P_{post} = 1.5\sin\delta_a = 1.0$$

$$\text{Solving for } \delta_a \text{ we get } \delta_a = 41.8$$

3.6 Modeling of the Power System

MATLAB Simulink is advanced software which is increasingly being used as a basic building block in many areas of the research. As such, it also holds great potential in the area of power system simulation. In this paper, I have taken a single machine power system as an example to illustrate the transient stability analysis in Simulink-based model. A self-sufficient model has been given with full details, which can work as a basic structure for an advanced and detailed study.

This model is useful for stability analysis but is limited to the study of transient stability of only the “first swing” or for small duration of time.

3.7 Generator modeling

A generator is an electrical component which converts mechanical energy of the prime mover to electrical energy. The different generators have different rating. We normally use the synchronous generator to generate power in grid. These generators disturbed due to different factors and withstand or not withstand this disturbance. Stability refers to the ability of the synchronous generator to remain in synchronism. IF after a disturbance the generator loss its synchronism it is said to be unstable. Swing curve can be used to see how stable the generator will be after a disturbance. It is basically a plot of rotor angle with respect to time.

The model of the synchronous generator is derived from the swing equation. The swing equation states that the net torque, which causes acceleration or deceleration of the rotor of the synchronous generator, is the difference between the electromagnetic torque and mechanical torque applied to the generator [5]. What we need to understand is that event like faults, change of loads, switching operations and generation loss can lead to a disturbance in synchronism of the generator. Loss of synchronism means the rotor will be out of synchronous with stator. Swing curve determine how fast the rotor angle will come back to equilibrium after disturbance.

From swing equation

$$P_a = M\frac{d^2\delta}{dt^2} = M\frac{d^2\theta}{dt^2} = P_m - P_e \tag{3.45}$$

Where, P_m, P_e and P_a respectively are the mechanical, electrical and accelerating power in. We can therefore conclude that the rotor angular speed is equal to the synchronous speed only when $\frac{d\delta}{dt}$ is equal to zero.

The angle between rotor axis and field axis is called power angle/torque angle (δ). The angle δ is the angle of the internal emf of the generator and it dictates the amount of power that can be transferred.

$$\delta = \frac{1}{M}\iint Pm - Pe \tag{3.46}$$

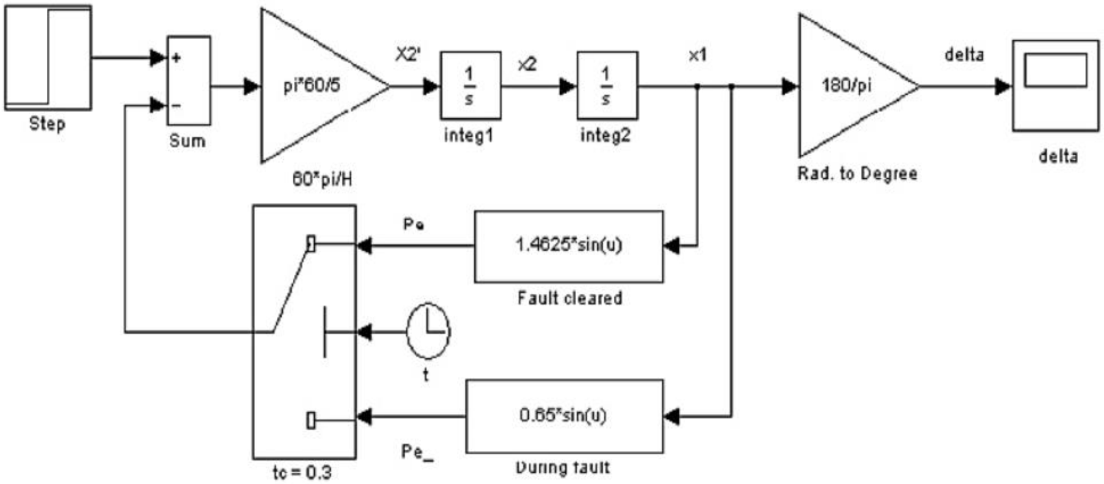


Fig.3. 26: Mathematical model for plot of δ verse time system

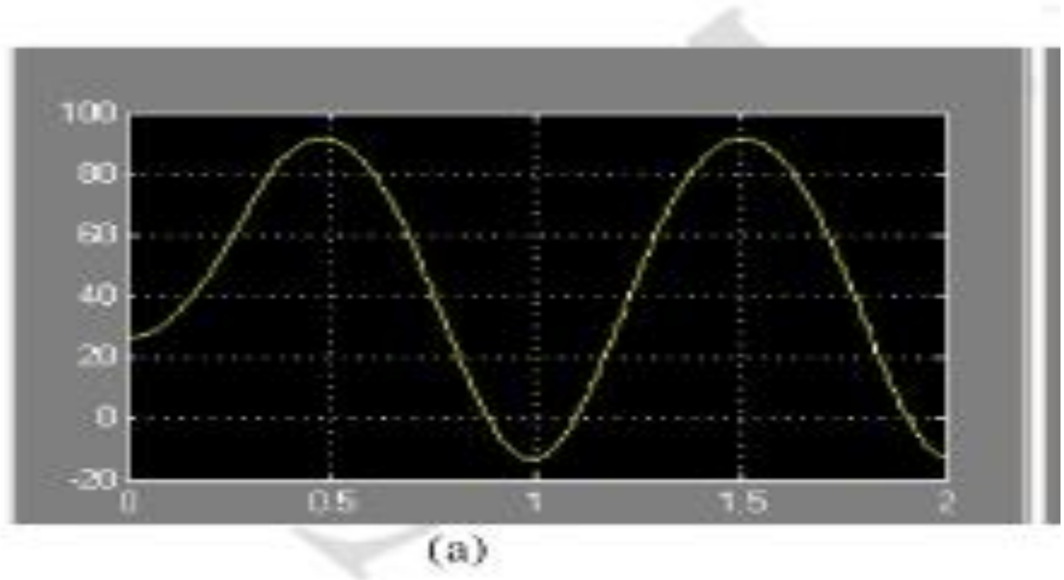


Fig.3. 27: Mat-lab results for plot of δ verse time for stable

The simulation result of single machine connected to infinite bus bar system by using Mathematical modeling of swing equation fig 3.27 result has obtained. This is clearly for the solution behavior desired. On the graph the first derivate is zero anywhere and system is able to return to its normal operation and stable but, the fig 3.28 the system not return to its normal operation and it is unstable and nowhere in the graph that first derivative is zero. Note that the graph is drawn the rotor angle vs. time for mathematical modeling with numerical value for stable and unstable condition

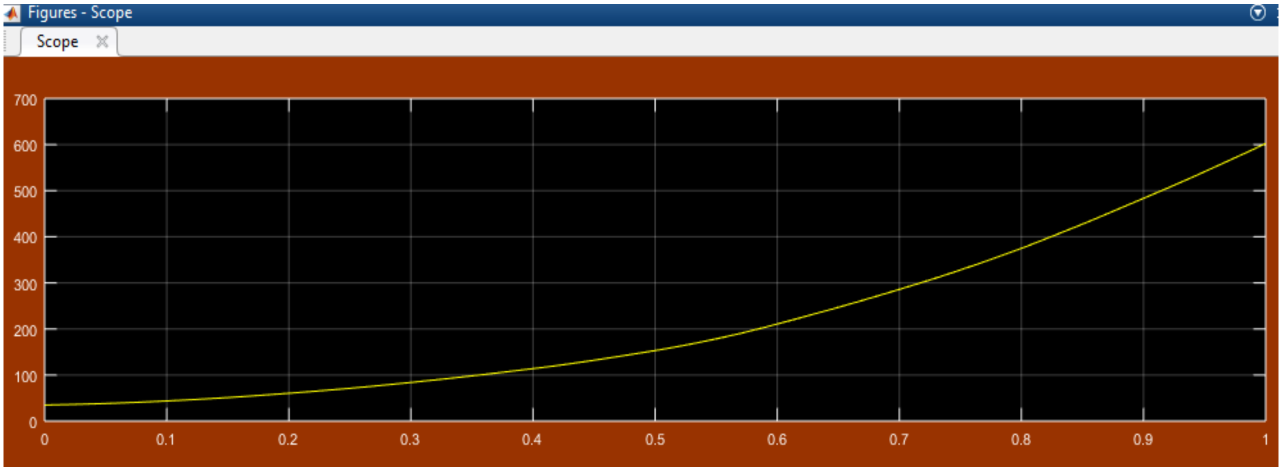


Fig.3. 28: Mat-lab results for plot of δ verse time for unstable

3.8 Transformer modeling

Transformers enable utilization of different voltage levels across the system. From the view points of efficiency and power-transfer capability, the transmission voltages have to be high, but it is not practically feasible to generate and consume power at these voltages. In modern electric power systems, the transmitted power undergoes four to five times voltage transformations between the generators and the ultimate consumers. Consequently, the total MVA rating of all the transformers in a power system is about five times the total MVA rating of all the generators [2].Transformers may be either three-phase units or three single-phase units. The latter type of construction is normally used for large EHV transformers and for distribution transformers. Large EHV transformers are of single-phase design due to the cost of spare, insulation requirements, and shipping considerations. The distribution systems serve single-phase loads and are supplied by single-phase transformers [24].

Transformer is a device for changing the voltage of A.C supply; it consists of two coil, called primary and secondary coils, wound round a soft iron core that is more of sheets of soft iron insulated from each other to reduce heat losses, such soft iron core is found to be laminated [14]. An alternating current applied at the terminals of the primary coil sets up an alternating magnetic flux in the core. This induces an e.m.f in the secondary coil. The induced e.m.f of the secondary coils depends on the e.m.f at the primary coil and the number of turns in both coil such that:

$$\frac{E_s}{\mathrm{E_p}} = \frac{N_S}{\mathrm{N_P}} \tag{3.47}$$

Where:

$$\frac{E_S}{E_p} = \frac{\text{Secondry e.m.f}}{\text{primary e.m.f}} \tag{3.48}$$

$$\frac{N_S}{N_p} = \frac{\text{number of turns in secondary coil}}{\text{number of turns in primary coil}} \tag{3.49}$$

When, the number of turn in the secondary coil ($\mathrm{N_s}$) is greater than the number of turns in the primary coil ($\mathrm{N_p}$) that is ($\mathrm{N_s} > \mathrm{N_p}$) the transformer will provide a higher emf at secondary coil than the primary coil, then the transformer is step up. This transformer is used in power station, to increase the emf before it is feed into the power transmission lines [5].

For step down transformer:-This is when the number of turns in the secondary ($\mathrm{N_s}$) is less than the number of turns in the primary ($\mathrm{N_p}$).

That is, ($N_s < N_p$) this means that the transformer will provide a lower e.m.f of the primary coil than the secondary coil. This is a step down transformer which is used to reduce the high voltages to the lower voltage that is usable in the home [23]. That is transformers are designed so that energy loses are reduced to a minimum level. This is achieved by:

- Making the coils with wire of low resistance
- Using a soft iron core
- Laminating the core to reduce energy losses due to eddy currents that is unwanted induced currents.
- Designing an efficient core

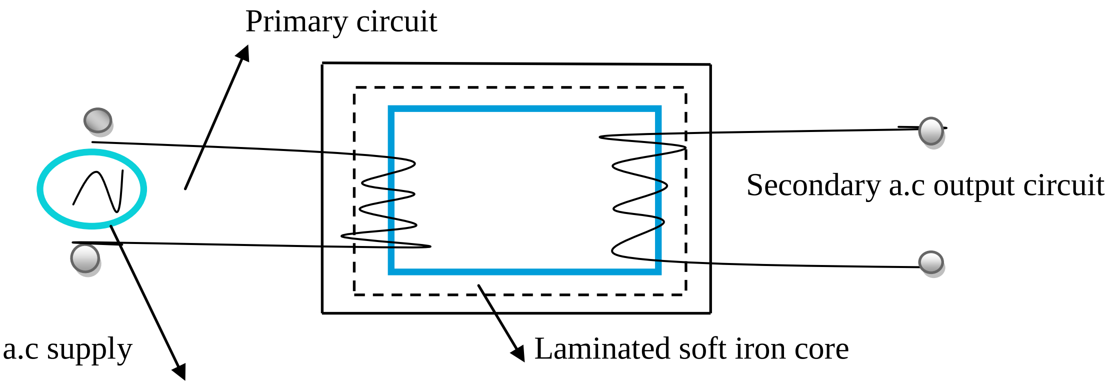


Fig.3. 29: Principle of transformer diagram

If N_1 = No of turns in primary (N_p)

N_2 = No of turns in secondary (N_s)

φ_m = maximum flux in core in Weber

$$= B_m * A \tag{3.50}$$

$$\text{Average rate of change of flux} = \frac{\emptyset_m}{1/4f} \tag{3.51}$$

$$= 4f\emptyset_m \frac{\text{wb}}{\text{s}} \text{ or volts} \tag{3.52}$$

If flux $\emptyset_m$ varies sinusoidally, then rms value of induced emf is obtained by multiplying the average value with form factor

$$\frac{\text{Rms value}}{\text{Average value}} = 1.11 \tag{3.53}$$

That is r.m.s, value of emf/turn = 1.11* $4f\emptyset_{\boldsymbol{m}}$ $=4.44f\emptyset_{\boldsymbol{m}}$ volts (3.54)

The r.m.s value of the e.m.f in primary is

$$E_1 = 4.44f N_1 \emptyset_{\boldsymbol{m}} = 4.44f N_1 B_m A \quad (3.55)$$

Similarly r.m.s value of the e.m.f in secondary is

$$E_2 = 4.44f\emptyset_{\boldsymbol{m}} = 4.44f N_2 B_m A \quad (3.56)$$

It is seen from equation (3.55) and (3.56) that

$\frac{E_1}{N_1} = \frac{E_2}{N_2} = 4.44f\emptyset_{\boldsymbol{m}}$ it means that e.m.f is the same in both the primary and secondary windings. But in an ideal transformer on no load $V_1 = E_1$ and $E_2 = V_2$ (3.57)

$\frac{E_2}{E_1} = \frac{N_2}{N_1}$=K, this constant is the voltage transformation ration. That is if $N_2 > N_1$ or $N_s > N_p$ then K >1Then transformer is a step- up transformer. Similarly, if $N_2 < N_1$, or $N_s < N_p$ then K < 1 then the transformer is a step-down transformer [7].

For ideal transformer;

Input V_A=output V_A

$$V_1 I_1 = V_2 I_2, or \frac{I_2}{I_1} = \frac{V_1}{V_2} = \frac{1}{K} \quad (3.58)$$

That is the currents are therefore, inverse ratio of the (voltage) transformation ratio. AB is primary winding having N_1 turns; BC is secondary winding having N_2 turns, Neglecting iron loss and no load currents;

Then $$\frac{V_2}{V_1} = \frac{N_2}{N_1} = \frac{I_1}{I_2} = K \quad (3.59)$$

The current in section CB is vector difference of I_2 and I1 but as the two current are practically in phase opposition, the resultant current $(I_2 - I_1)$ where I_2 is greater than I_1.

3.9 Load modeling

The electrical load connected to the synchronous generator is of two types: consumer load and ballast load. The change in the total electrical load is due to changes in both the consumer and ballast load.

$$\Delta\bar{P}_e = \Delta\bar{P}_B + \Delta\bar{P}_D \quad (3.60)$$

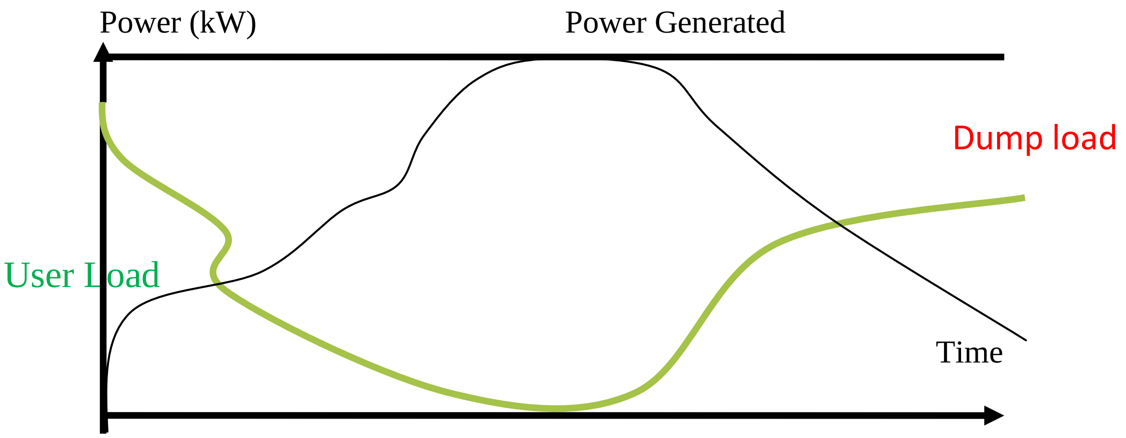


Fig.3. 30: Power Generated=User load +Ballast load [6]

3.9.1 Ballast load modeling

The ballast load is a low priority, resistive load that accepts the surplus energy generated. Its primary purpose is to counteract the change in the consumer load. When certain amount of load is removed from the consumer load, the same amount of load must be accepted in the ballast load and vice versa. The capacity of the ballast load is determined by taking into consideration the ideal condition that the consumer load is zero at some instant. When the entire consumer load is suddenly out, all the output of the synchronous generator should be accepted by the ballast load. At this condition

$$P_{e\text{-Rated}} = P_B \tag{3.61}$$

The value of total ballast resistor is given by

$$R_B = \frac{V^2_{LL}}{\text{Pe-Rated}} \tag{3.62}$$

3.9.2 Load response to frequency deviation

In general power system loads are a composite of variety of electrical devices. For resistive loads, such as lighting and heating loads, the electrical power is independent of frequency. In the case of motor loads, such as fans and pumps, the electrical power changes with frequency due to changes in motor speed. How a load is sensitive to frequency depends on the composite of the speed-load characteristics of all the driven devices [21]. The overall frequency-dependent characteristics of a composite load can be expressed as

$$\Delta\bar{P}_D=\Delta\bar{P}_L + D\Delta\bar{\omega}_r \tag{3.63}$$

The load damping constant is expressed as percent change in load for one percent change in frequency. Typical values of D are 1 to 2 percent. A value of D=2 means that change in divided by percent change in frequency [21].

The system block diagram including the effect of the load damping is shown below

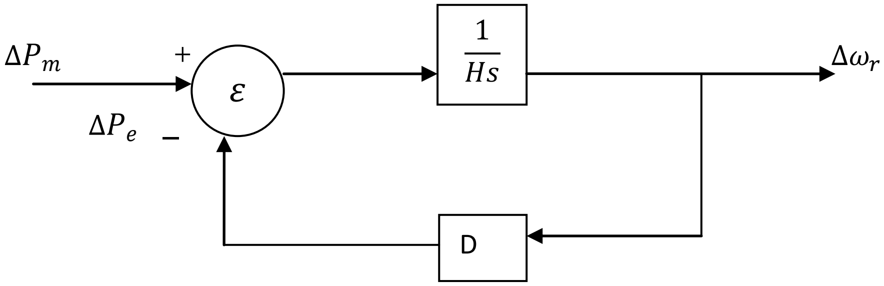


Fig.3. 31: Generator with load damping effect

Ballast load is a pure resistive load; hence the effect of damping is neglected for ballast load. The change in electrical load can be rewritten as

$$\Delta\bar{P}_e = \Delta\bar{P}_B + \Delta\bar{P}_l + \Delta D\bar{P}\omega_r \tag{3.64}$$

In a power system normally more than two generators operate in parallel. The machines may be located at different places. A group of machines located at one place may be treated as a single machine. Machines not connected to the same bus but separated by lines of low reactance, may be grouped into one large machine. The capacity of the system is so large that its voltage & frequency may be taken as constant. The connection or disconnection of a single small machine on such a system would not affect the magnitude and phase of the voltage and frequency.

Such a system of constant voltage and constant frequency regardless of the load is called infinite bus bar system or simply infinite bus. Physically it is not possible to have a perfect infinite bus. An infinite bus is an ideal voltage source depending on the power demand on the grid system. The operation connecting a synchronous generator to the infinite bus is known as paralleling with the infinite bus.

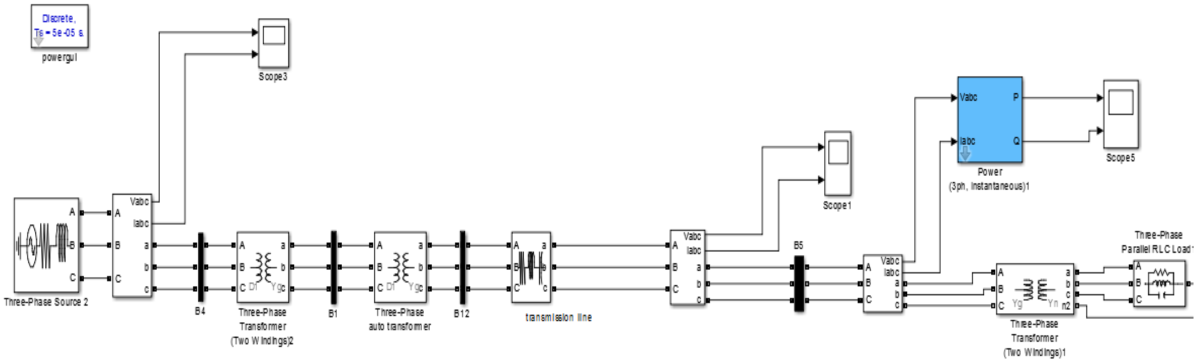


Fig.3. 32: The MATLAB Simulink model of single machine connected to infinite bus system without faults

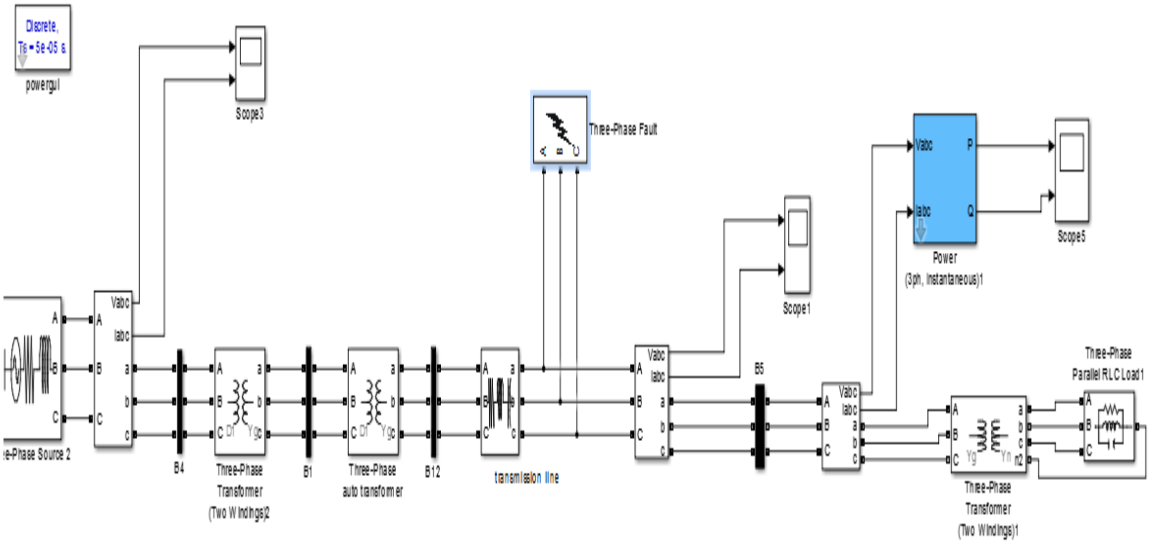


Fig.3. 33:The MATLAB simulink model of SMIB system without faults

3.10 Model of thyristors Controlled Series Compensator (TCSC)

TCSC basically comprises of the thyristor controlled reactor which is in parallel with capacitor and all the three are in three phases as shown in the fig 3.34 overall effective Impedance is reduced by inserting capacitor in series with Transmission Line. A compensating capacitor is connected in series which cancels a portion of actual line Reactance.

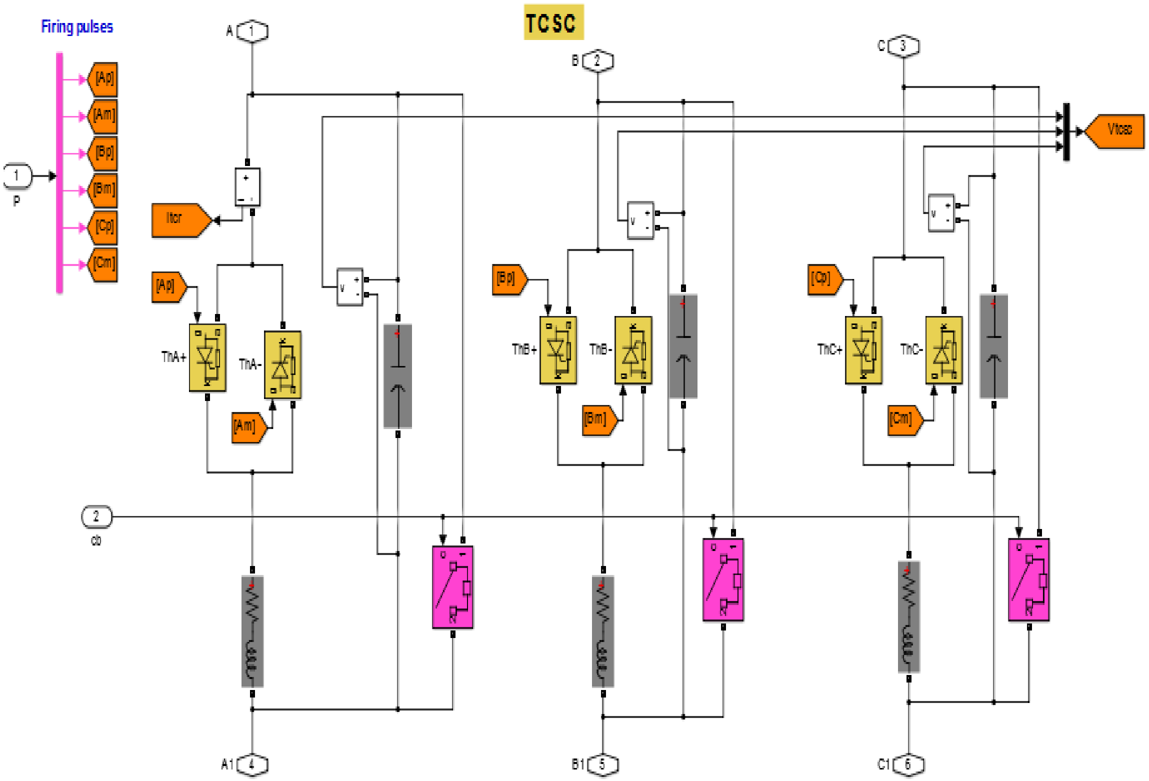


Fig.3. 34: The MATLAB Model of Internal structure of TCSC with firing pulses

Firing pulses have to be generated (controlled) for all of the three phases that is done with the combination of control unit and firing unit. Whenever the TCSC is operating in constant mode it basically utilizes the feedback voltage and current in order to calculate the impedance. We basically give it the reference impedance that is compared with the impedance calculated with the help of feedback voltage and current. How it doses?

We go to the control unit in which the voltage from TCSC and the line current feed to this unit.

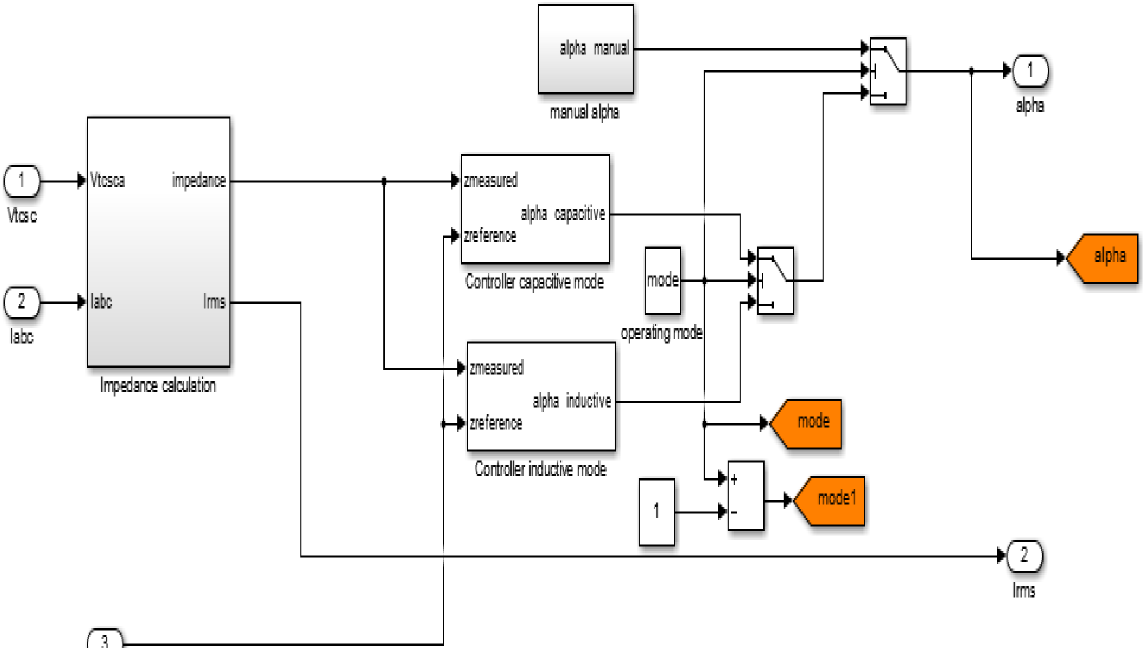


Fig.3. 35: The impedance calculation block in the control unit

In the control unit of TCSC there are two modes in which this TCSC work.

1. Capacitive mode
2. Inductive mode(reactive)

For capacitive mode the range for impedance values is approximately 120-136 Ohm. In the inductive mode the values is approximately 19-60 Ohm. The impedance calculation block calculates the impedance by using the TCSC voltage and line current as an input and given to PI controller. In the controlling unit there is separate controller for capacitive and inductive mode. The PI controller basically compare Z_{ref} with $Z_{measured}$ measured which is given by impedance calculation block and ultimately it generate the angle (α). This angle (α) given to the firing unit which has three inputs, alpha (which is calculated by the previous block the control unit), line current and I_{rms}. The firing circuit basically consists of three single phase PLL unit for synchronization with the line current shown in fig 3.36.

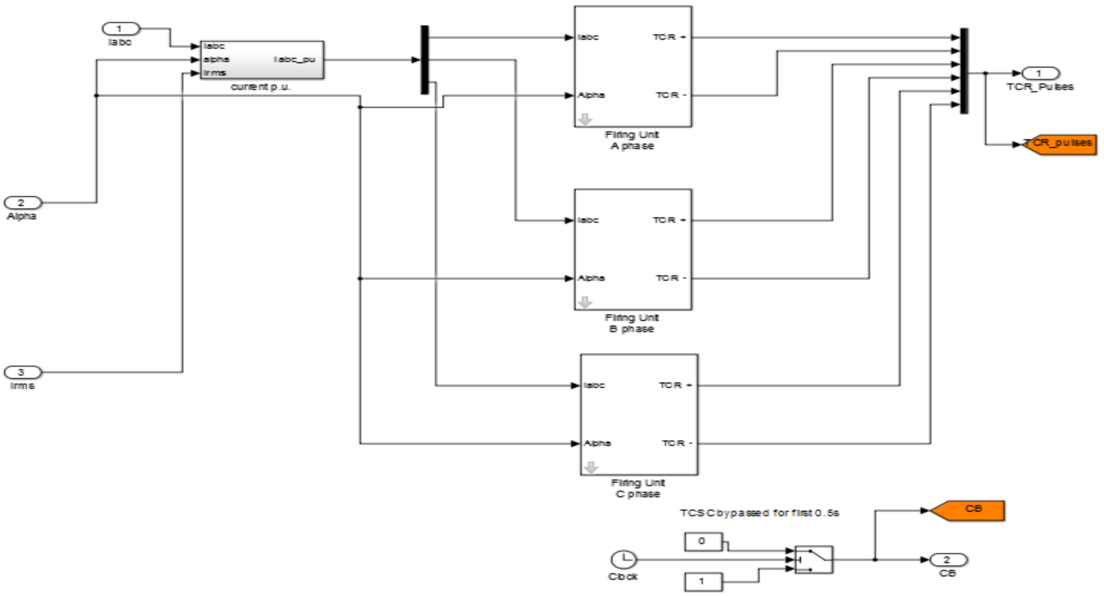


Fig.3. 36: The firing pulses of TCSC

One important point to be noted here is that it is the line current used for synchronization of PLL this one of the main difference between the series and shunt since, in control scheme of stat-com the line voltage used for synchronization.

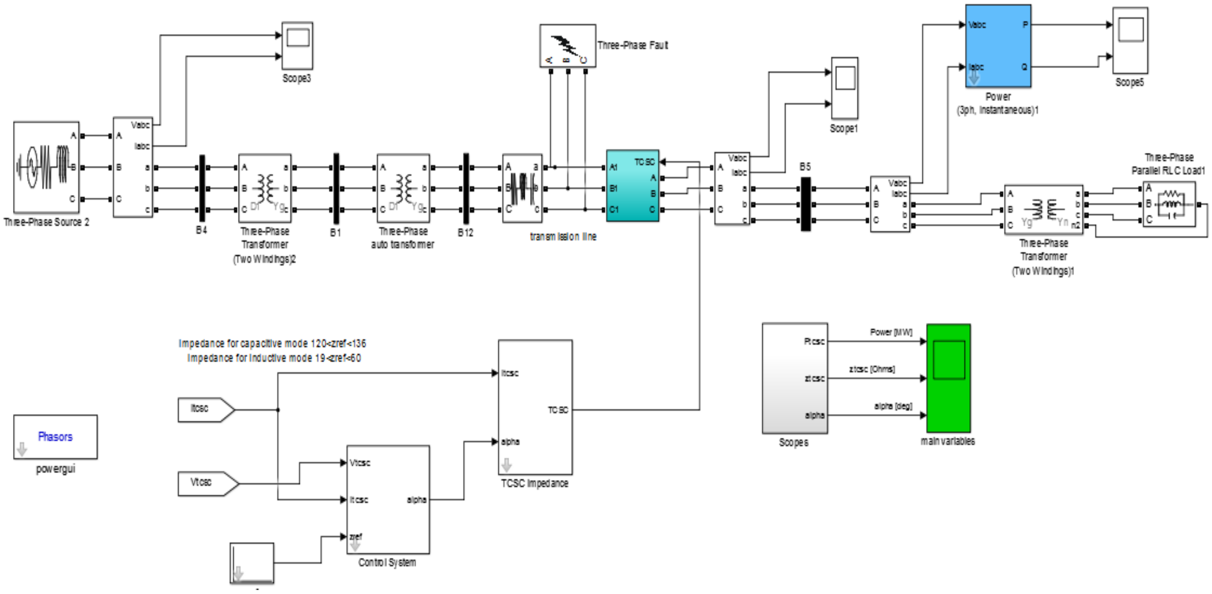


Fig.3. 37:The over all MATLAB simulink model ofpower system with TCSC

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Simulation Results

The simulation results of the model for power systems of single machine connected to infinite bus bar system is tested for three different cases.

1. When the power system is without fault
2. When the three phase fault is applied for the power system at different location
3. When the TCSC device is installed for the second case

When the system is without disturbance like; no application of large loads, no load is removed, and no fault the power system is stable. There is a balance between the generation voltage, frequency to the load and the simulation results shown below are the voltage and the current wave forms without the application of the three phase faults. For this case the generator is in synchronism and the system is delivering pure sinusoidal voltage and current. The frequency and the voltage from the grid side and the load side is balanced that system is in steady state. As can be shown in fig 4.1

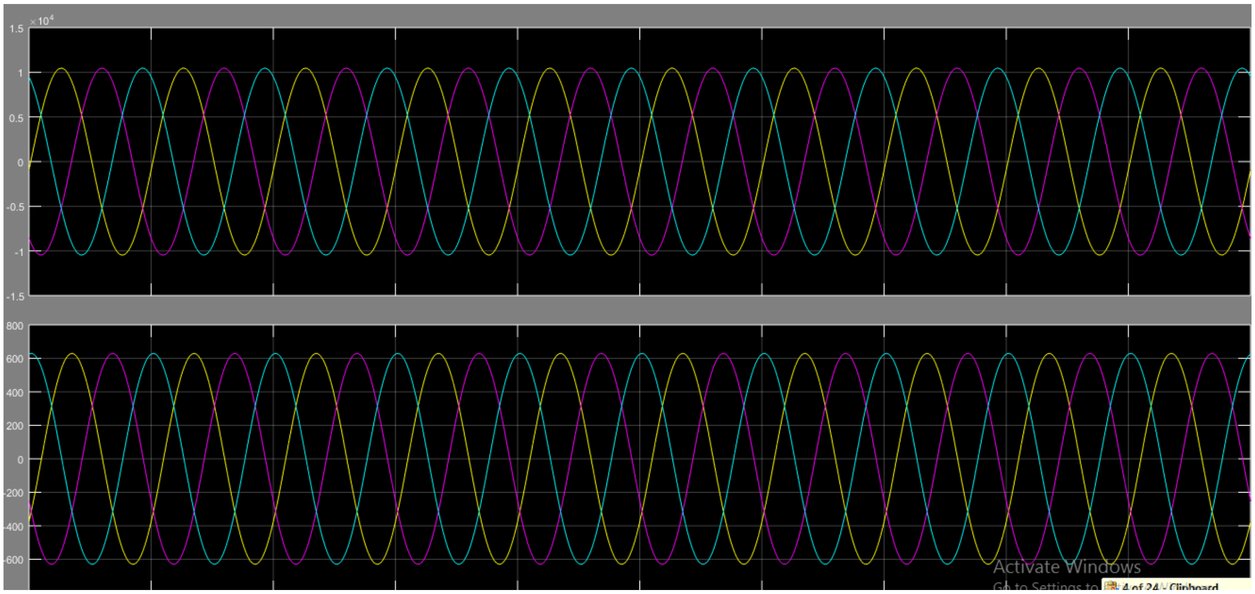


Fig.4. 1: Simulation results of the voltage and the current of the generator respectively

The field voltage of the generator were given by using bus bar to the transformer and the power transformer step up the voltage in order to reduce the line current which in turn reduces the loss and increased power efficiency. The simulation results show that the voltage and the current is pure sinusoidal wave form. The voltage and the current of the transmission line are shown below

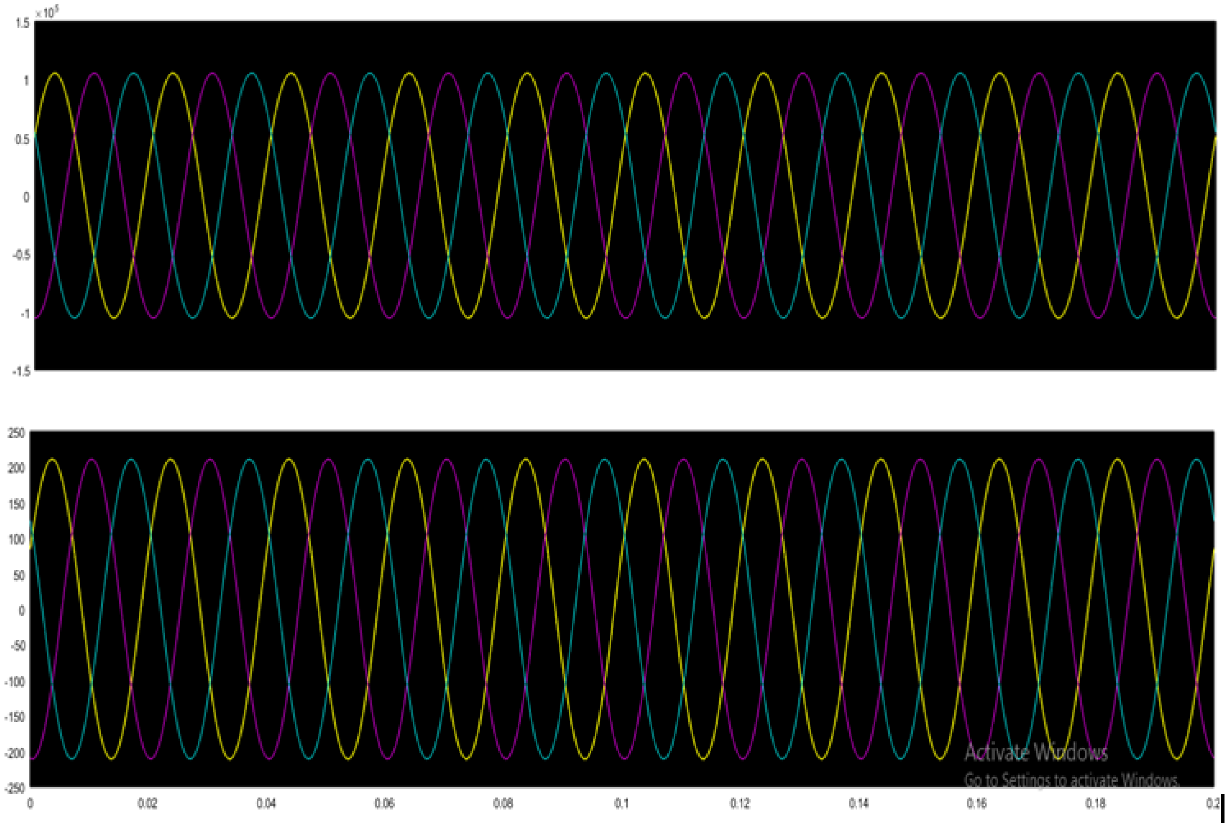


Fig.4. 2: Simulation results of the voltage and the current of the transmission lines respectively

There is small oscillation of the power during the first few second and then last and the power transmitted become constant. The power transmitted normally depends up on the reactance of the transmission line since; decreasing the line reactance of the transmission line increases the power transmitted to the load.

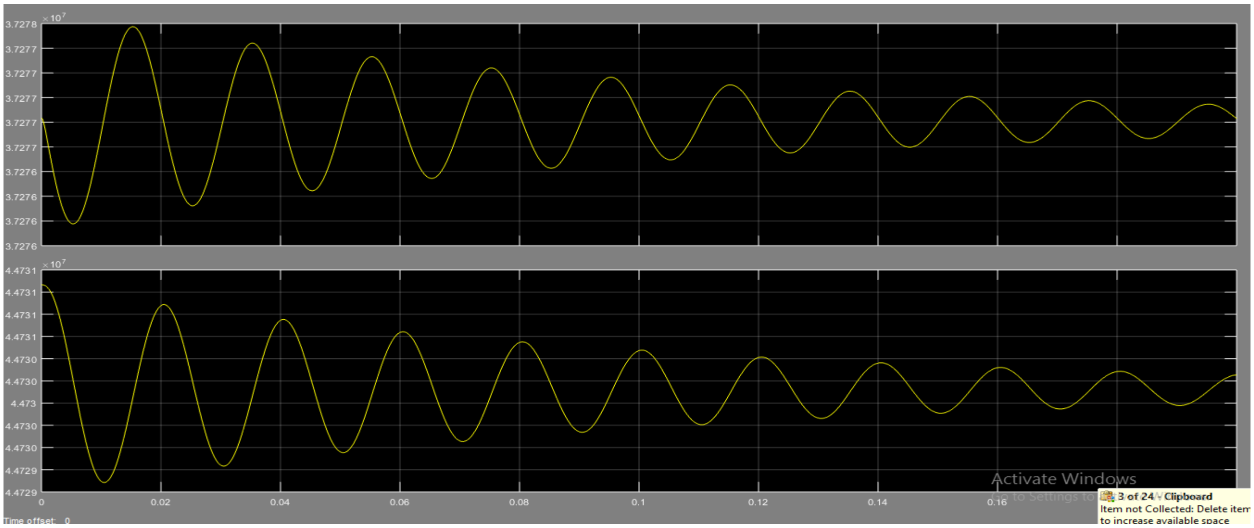


Fig.4. 3: Simulation results of active and reactive power delivered to the load respectively

When three phases fault is applied on the power system the system is disturbed and even the synchronous generator try to swing due to the mechanical torque and electrical are not balanced. The voltage sag happens and the current increase which, creates some disturbance on the power system. If this disturbance is not avoided by using some devices like capacitor which reduces the voltage regulation or by TCSC the system becomes unstable. This disturbance on the voltage and the current is shown in Fig 4.4

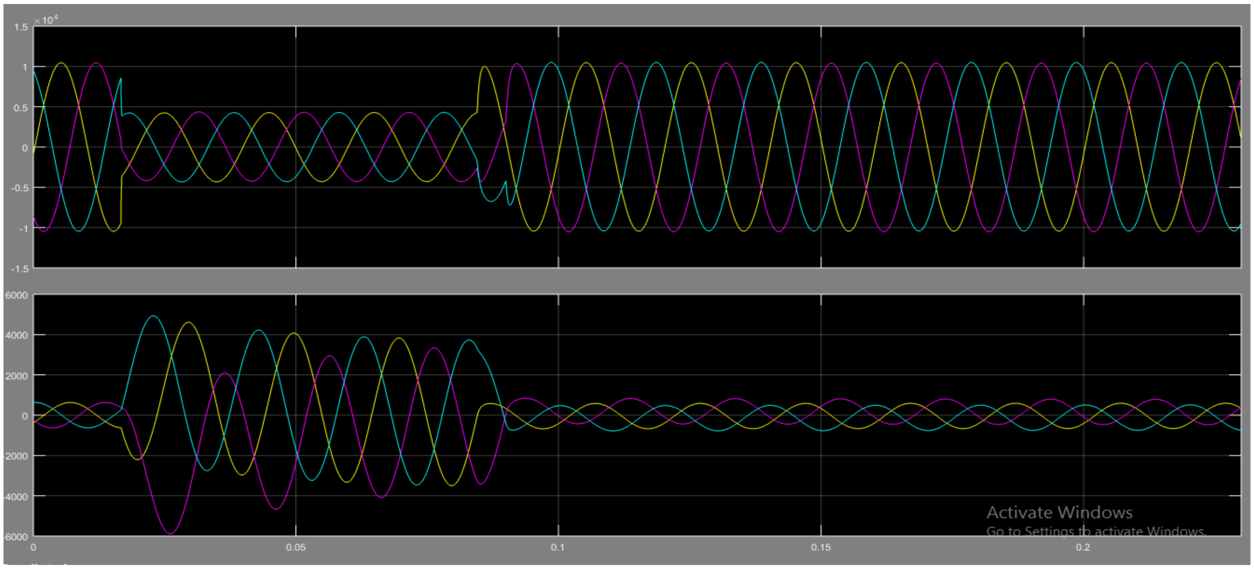


Fig.4. 4: Simulation results of the voltage and the current of the generator respectively when three phase fault at middle of transmission line

Firstly the generator is operating in normal condition but, suddenly when three phase fault happen at the middle of the transmission line the voltage sag happens. The generator first have a voltage of 13.8 KV at the instant three phase fault happens at the middle of transmission line it is reduced to around 5kV. The current were increased to approximately 4500A but, after the fault is cleared it returns to its normal operation. As can be seen in the fig (4.4) when the voltage sag happen the current increases rapidly till the fault is cleared and the system returns back to its normal operation as can be shown in Fig 4.5.when three phase fault happen at the middle of the transmission line the voltage interruption happens which lead zero power transfer. The Simulation results of the voltage and the current of transmission line shown below in Fig.4.5.

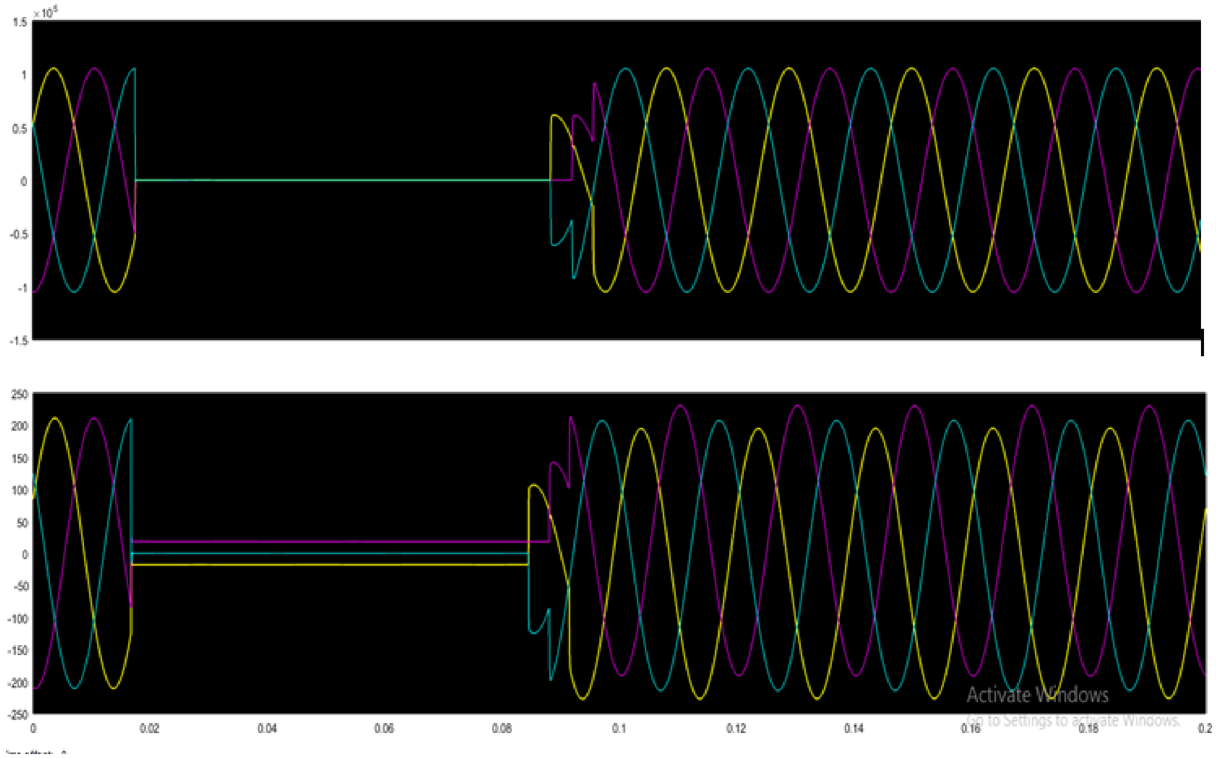


Fig.4. 5: Simulation results of the voltage and the current of transmission line when the fault is at the middle of the transmission line

When the three phase fault is applied to the transmission line disappearance of the supply voltage in all three phases happen and the current increases highly till the fault is cleared by the breaker. After fault is cleared the system returns to its normal operation and the voltage and current wave form is normal which is shown in fig.4.5.

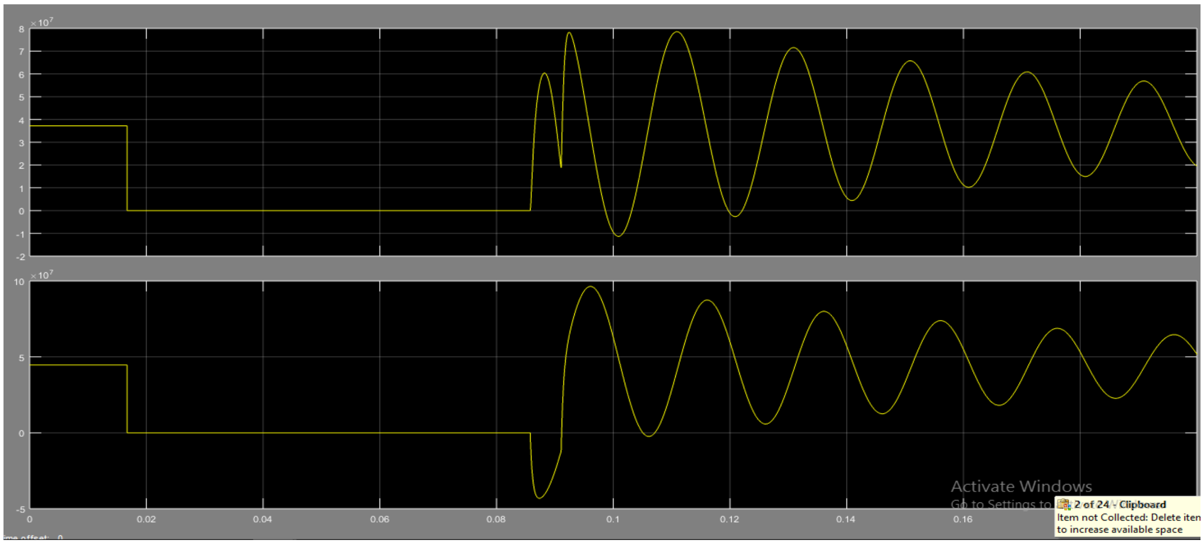


Fig.4. 6: Simulation results of active and reactive power for three phase fault at the middle of transmission line

When the fault is near the generator means before it is fed in to step up transformer the values of current is higher as compared to after step up inorder to reduce loss. The fault near the generator is severe compared to the transmission line and near the load. The three phases of the voltage have got interruptions during the fault and the current is also disturbed but, after fault clearance the system back to it nominal value. For fault happen near the generator the active and reactive power is shown below.

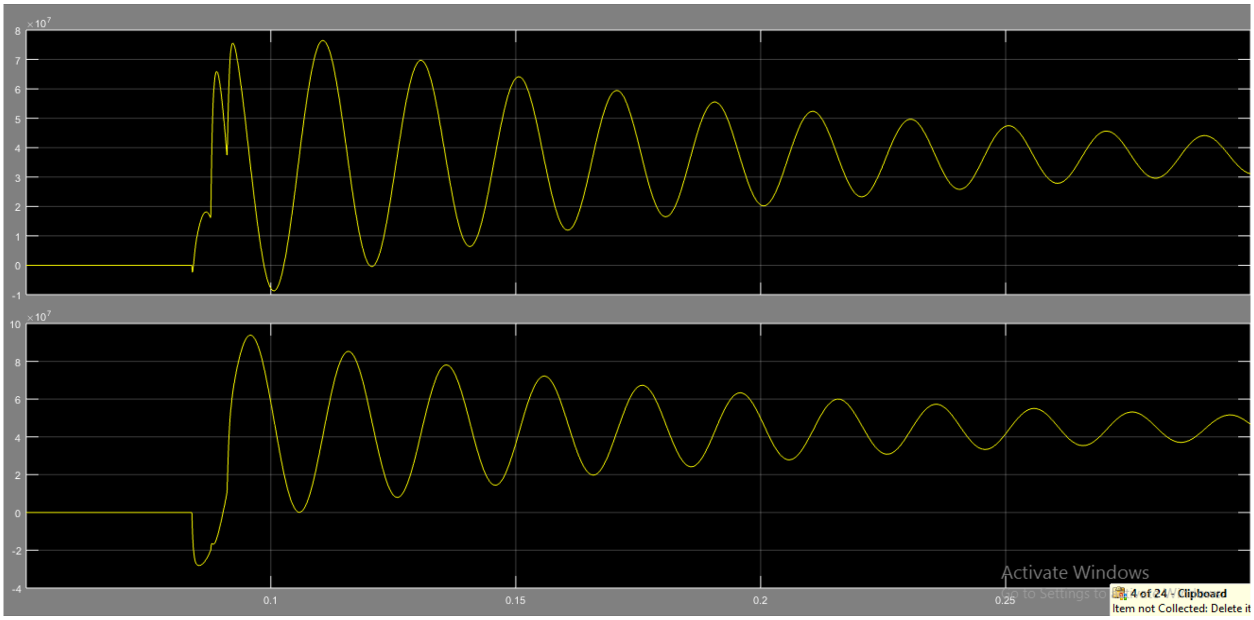


Fig.4. 7: Simulation results of Active and Reactive power for fault near the generator

As it can be seen from the simulation results of fig (4.7) when three phase short circuit happens near the generator it is severe that the generator gets isolated from the system and the power transferred is zero.This disturbance happens during the fault for a few second up to which the fault is cleared and then the system returns to its normal operation. The power system return to to its nominal value but, due to large loads the active power is damping and reacive power isoscillated and then becomes constant.

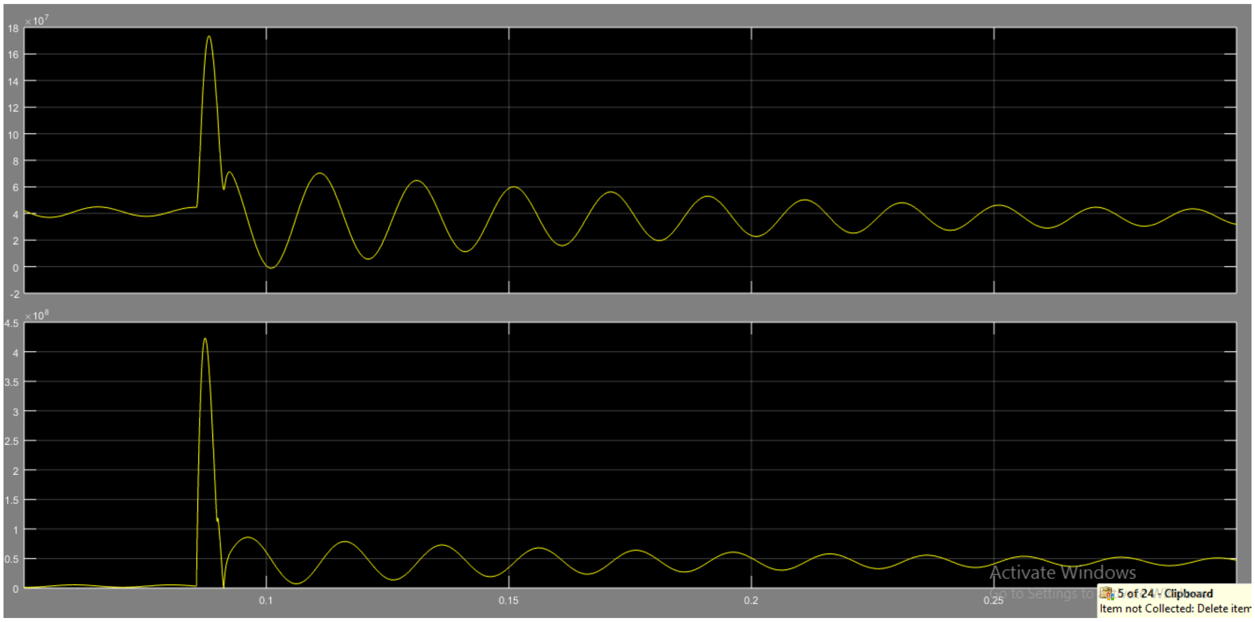


Fig.4. 8: Simulation results of active and reactive power for fault near the near the load

When the TCSC device is applied in the power system modeled with TCSC under three phase fault condition it starts to generate the firing angle in the control unit block diagram. Firing pulses have to be generated (controlled) for all of the three phases that is done with the combination of control unit and firing unit. Whenever the TCSC is operating in constant mode it basically utilizes the feedback voltage and current in order to calculate the impedance. We basically give it to the reference impedance that is compared with the impedance calculated with the help of feedback voltage and the line current. The PI controller basically compare $Z_{ref}$with $Z_{measured}$ measured which is given by impedance calculation block and ultimately it generate the angle (α). The decrement of this angle results to decrease the impedance

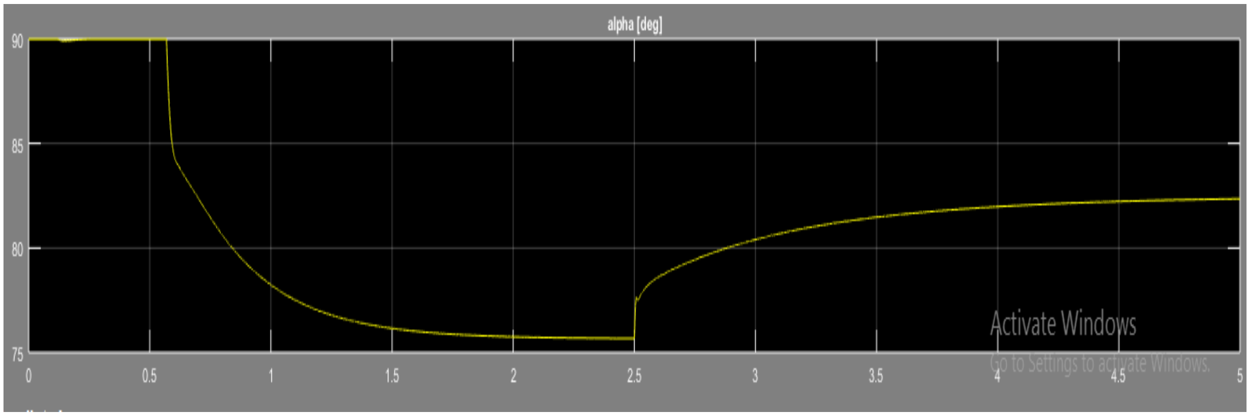


Fig.4. 9: Simulation results of firing angles of thyristor controlled reactor with TCSC

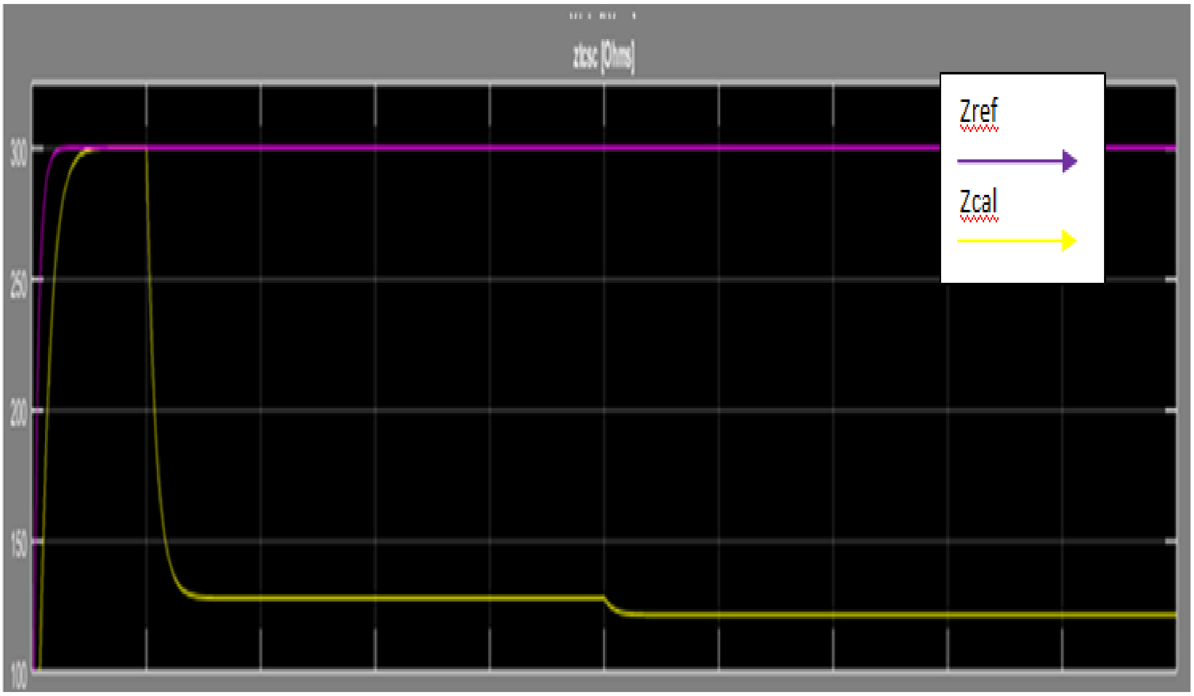


Fig.4. 10: Simulation results Impedance for reduction of firing angle with TCSC

The active power and reactive power is oscillation is decreased as can be shown in fig 4.10. This is due to the generated (controlled) firing pulses for the three phases that is done with the combination of control unit and firing unit. Whenever the TCSC is operating in constant mode it basically utilizes the feedback voltage and current in order to calculate the impedance. We basically give it the reference impedance that is compared with the impedance calculated with the help of feedback voltage and current. The simulation results show that initially the power system is operating at an angle of $90^0$and low impedance then as angle is reduced the value of the impedance is reduced and thereby power transfer capability of the system is increased and oscillation is effectively reduced.

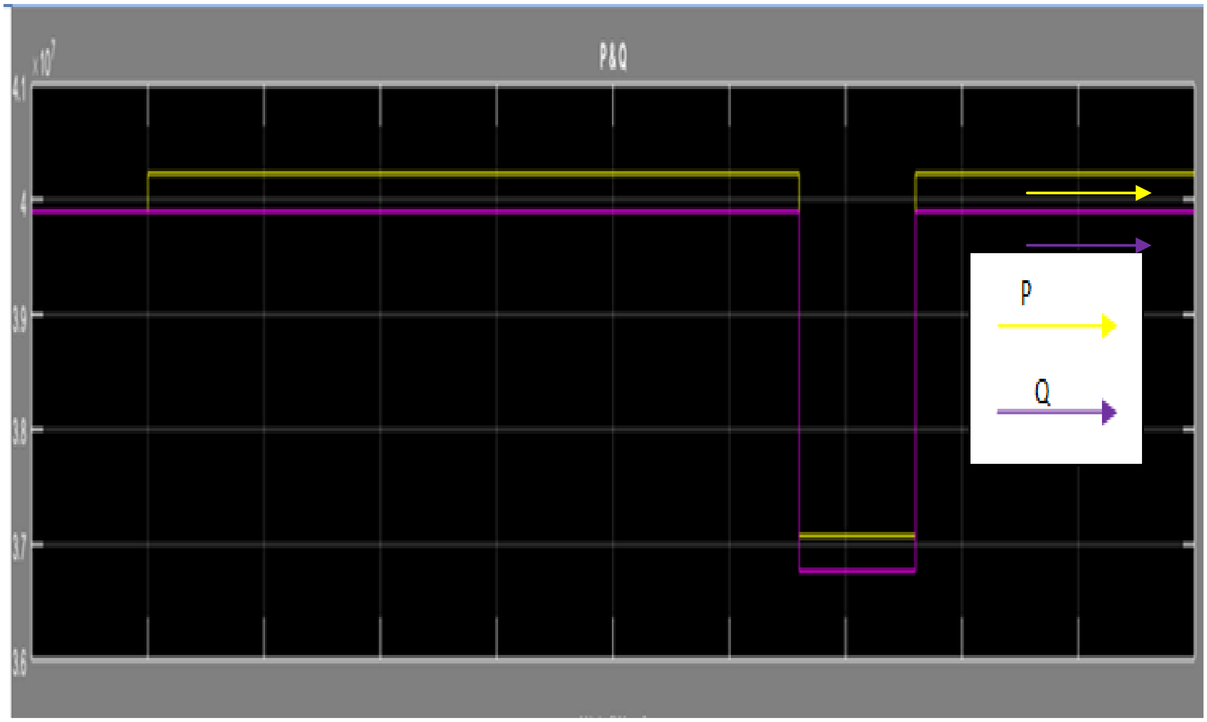


Fig.4. 11: Simulation results of active and reactive power, with TCSC

From the simulation results shown in fig 4.11 with TCSC the active and reactive power of the system oscillations are effectively damped out as compared to the simulation results obtained without TCSC. The Power transfer capability is also increased due to the reduction of impedance. This is done by changing the firing angle of the thyristor controlled reactor.

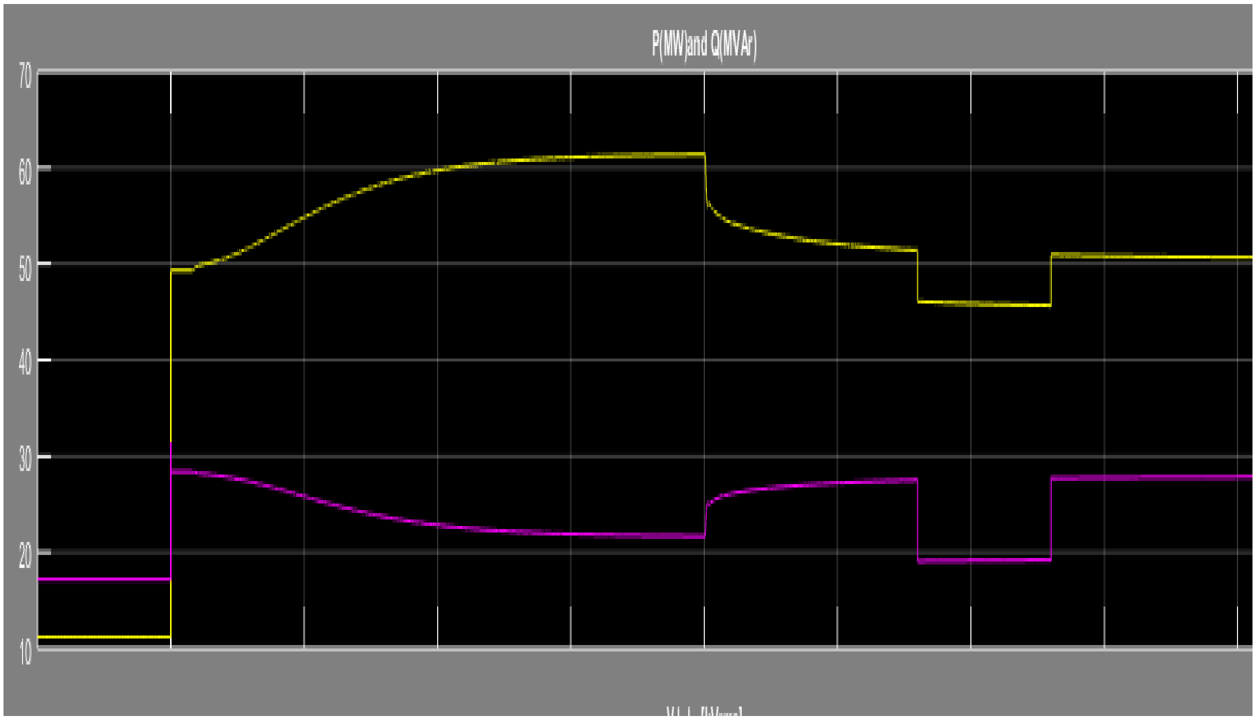


Fig.4. 12: Simulation results of active and reactive power, with fault under TCSC

4.2 Discussions

After modeling and simulating the power system using the MATLAB softwere variation of the real time voltage, current and power at buses for fault and without fault is illustrated. The result shows that active and reactive powers at bus got oscillated due to large fault on the system and which keep continuing for almost long second. Because of three phase faults the active power oscillations are more compared to reactive power oscillations.

The TCSC can operate in both capacitive and inductive mode, although the latter is rarely used in practice. Since the resonance for this TCSC is around 58deg firing angle, the operation is prohibited in the firing angle range 49deg - 69deg. The capacitive mode is achieved with firing angles 69-90deg.

The impedance is lowest at 90deg, and therefore power transfer increases as the firing angle is reduced. In capacitive mode the range for impedance values is approximately 120-136 Ohm. Comparing with the power transfer for uncompensated line, the TCSC enables significant improvement in power transfer level.

To change the operating mode (inductive/capacitive) toggle switch in the control block dialog is used. The inductive mode corresponds to the firing angles 0-49deg.

In the inductive operating mode, the range of impedances is 19-60 Ohm, when TCSC operates in the constant impedance mode it uses voltage and current as a feedback for calculating the TCSC impedance. The reference impedance indirectly determines the power level, although an automatic power control mode could also be introduced.

The firing circuit uses three single-phase PLL units for synchronization with the line current. Line current is used for synchronization, rather than line voltage, since the TCSC voltage can vary widely during the operation. Running the simulation and observing the waveforms on the main variables scope block, the TCSC starts with alpha at 90deg to enable lowest switching disturbance on the line. Finally the simulation results clarify that TCSC enables tracking of the reference impedance and increase the power transfer capability of the system.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATION

5.1 Conclusions

This thesis presents the study of transient stability analysis with and without TCSC. In this thesis, a systematic procedure for modeling, simulation of TCSC controller for enhancing power system stability is presented. Equal area criteria for different cases area further studied and analyzed. A MATLAB/SIMULINK model was developed for a single-machine infinite bus power system with TCSC model. Accordingly, it is seen that a three phase short circuit fault at the generator end is found to be most severe. Fault at the middle of transmission line is more severe than the same fault occurring at the load side. System with TCSC shows a much faster operation in damping post fault oscillation rather than in the system without controller.

Moreover, the controller is tested on power system subjected to large as well as small disturbances. The simulation results show that, the TCSC controller improves stability performance of the power system and power system oscillations are effectively damped out.

Therefore, the stability analyses in a given power system is a very important aspect to keep the system at a reliable position which can further help during the designing step of a new transmitting and generating plants. In addition, this study is supportive and suggestive in analyzing, voltage levels and transfer capability between systems. Therefore, this supplement idea of learning and teaching software MATLAB/ SIMULINK based technique for power system stability studies will provide a very simple and valuable tool for numerical solutions as well as simulation facilities in the field of power system and its analysis.

5.2 Recommendation

The Ethiopian Electric Power should work a lot on the whole power system, from generation to distribution, to enhance the power system stability problem, voltage variation and frequency variation of its electric power supply. Most of the generations designed were not capable of handling the present load due to increasing demand of electricity. Since Building new generating station and transmission is difficult due to different factors like cost, availability of resource, environmental factors, so the existing capacity should be enhanced. TCSC is capable of increasing power transfer capability by reducing the impedance and controlling the angle between end line voltages and thus can be highly recommended for its real implementation in the specific power system. However, this TCSC are ineffective in controlling the overall voltage profile. So, shunt device like D-STATCOM should be modeled and analyzed.

The Ethiopian Electric Power should work a lot in order to install this newly emerging FACTS device technology. Because it is technology transfer and they are effective and efficient in

- ✓ Controlling Voltage profile
- ✓ Changing the impedance
- ✓ Controlling firing angle of the transmission line

Finally due to the natural pandemic disease named, covid-19, we faced a lot of challenges in this year which hindered easy mobility in collecting data from the sites.

Power System Stability analysis with the help of Matlab/Simulink/SimPower Systems has been investigated in this research work. Power system Stability problem is real time issue, so there is a need to focus on this topic with more attention in order to avoid instability in the system during further study.

Since power systems are Non-linear and complex, the modeling has to be further analyzed with other worldwide utilizing software.

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APPENDICES

Appendix I: IEEE Std. Definitions of Terms

Power disturbance: Any deviation from the nominal value (or from some selected thresholds based on load tolerance) of the input AC power characteristics.

Power quality: The concept of powering and grounding sensitive equipment in a manner that is suitable to the operation of that equipment.

Power system stability: is the ability of an electric power system to regain a state of operating equilibrium after being subjected to a physical disturbance.

Transient stability: the ability of the system to regain synchronism after a large disturbance. This occurs due to sudden change in application or removal of large load, line switching operation fault on the system, sudden outage of the line or loss of excitation.

Thyristor Controlled Series Capacitor (TCSC): is a series FACTS device which allows rapid and continuous changes of the transmission line impedance.

The steady-state stability limit:-Is the maximum amount of power that can be transferred from the source to the load without the system becoming unstable when the load is increased gradually under steady state condition.

Transient stability limit: - Is the maximum power that can be transferred without the system becoming unstable when a sudden or large disturbance occurs.

Equal area criterion: technique by which the stability of a single machine connected to infinite bus can be examined under transient condition without solving the swing equation.

Critical clearing angle: the maximum clearing angle at which the system able to return to its normal operation after having been disturbed. For system to be stable actual clearing time of circuit breaker is smaller than critical values.

Critical clearing time: the maximum time that circuit breaker opens to clear the fault. If the actual clearing time is less than critical clearing time system is stable.

Voltage stability*:* ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance for a given initial operating condition.

Sag: A decrease to between 0.1 and 0.9 pu in rms voltage or current at the power frequency for durations of 0.5 cycle to 1 min. Typical values are 0.1 to 0.9 pu.

Swell: An increase in rms voltage or current at the power frequency for durations from 0.5 cycles to 1 min. typical values are 1.1–1.8 pu.

Overvoltage: When used to describe a specific type of long duration variation, refers to a measured voltage having a value greater than the nominal voltage for a period of time greater than 1 min. The typical values are 1.1–1.2 pu.

Frequency stability: ability of a power system to maintain steady frequency following a severe system upset resulting in a significant imbalance between generation and load.

Voltage fluctuation: A series of voltage changes or a cyclical variation of the voltage envelope.

Waveform distortion: A steady-state deviation from an ideal sine wave of power frequency principally characterized by the spectral content of the deviation.

Nonlinear load: Steady-state electrical load that draws current discontinuously or whose impedance varies throughout the cycle of the input ac voltage waveform.

Swing equation: States that the net torque, which causes acceleration or deceleration of the rotor of the synchronous generator, is the difference between the electromagnetic torque and mechanical torque applied to the generator.

Appendix II: Electrical Models for Simulation

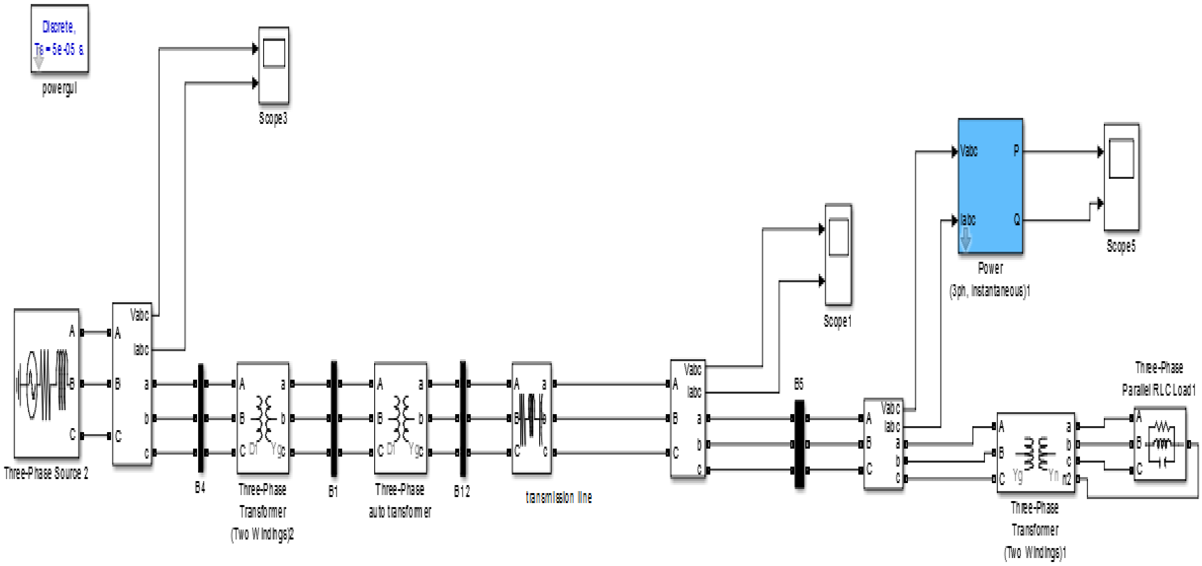

Figure B-1 MATLAB simulation Results of power system without faults

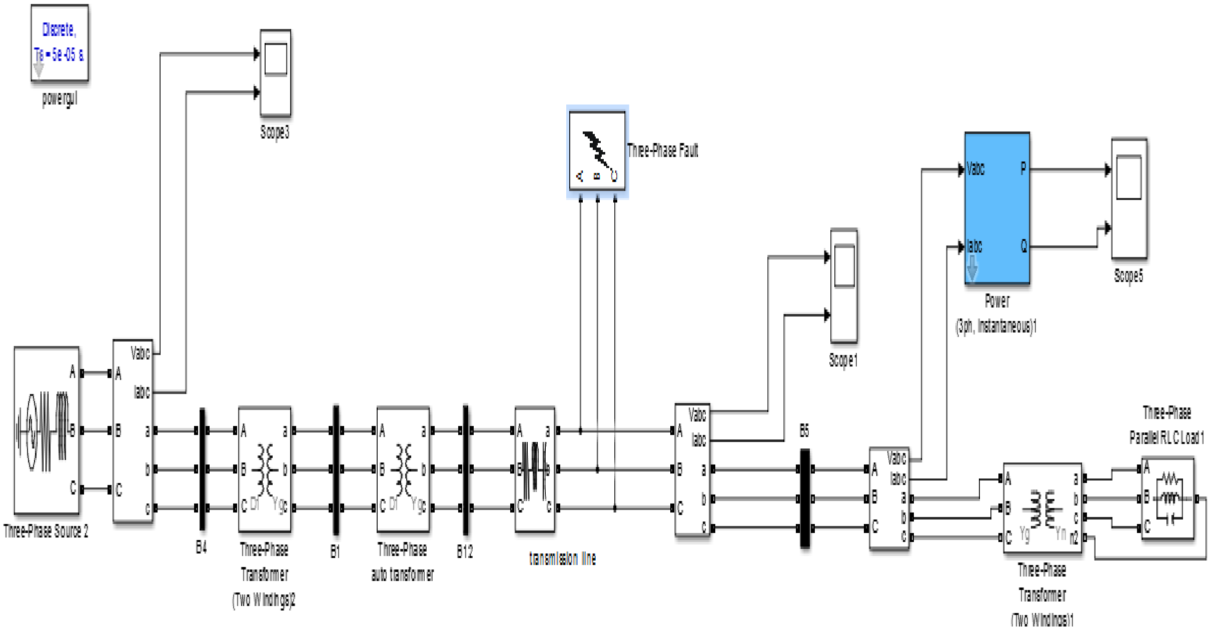

Figure B-2 MATLAB model of the power system without TCSC

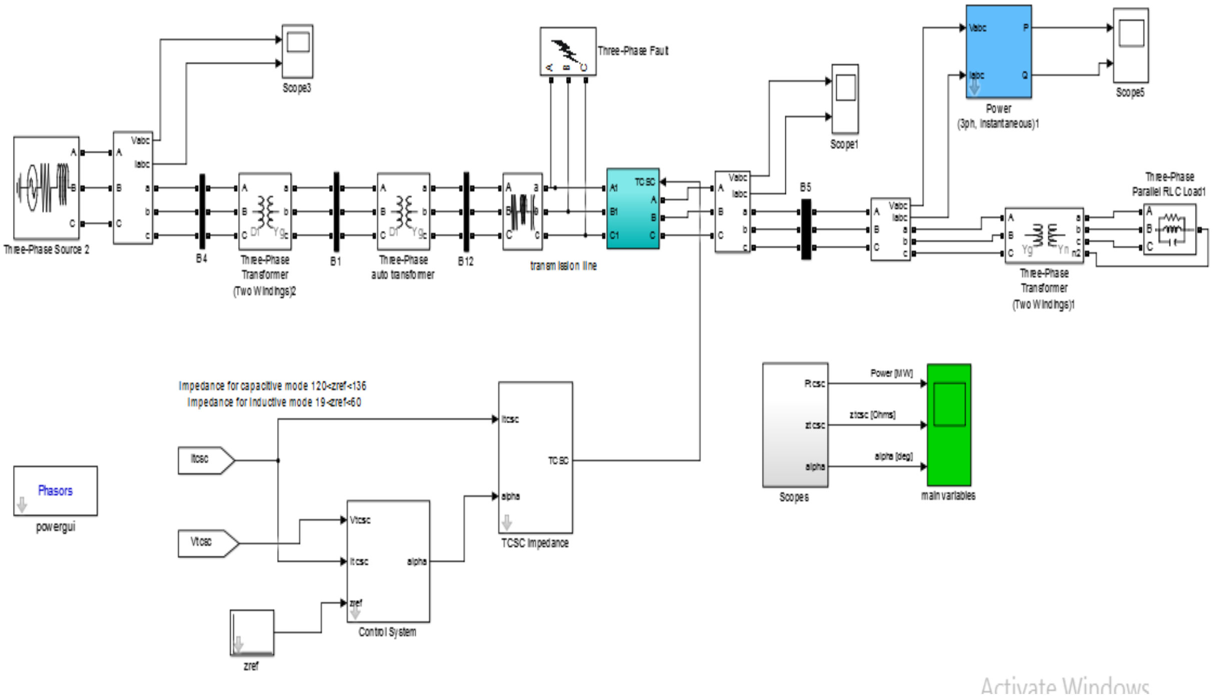

Figure B-3 MATLAB model of the power system with TCSC

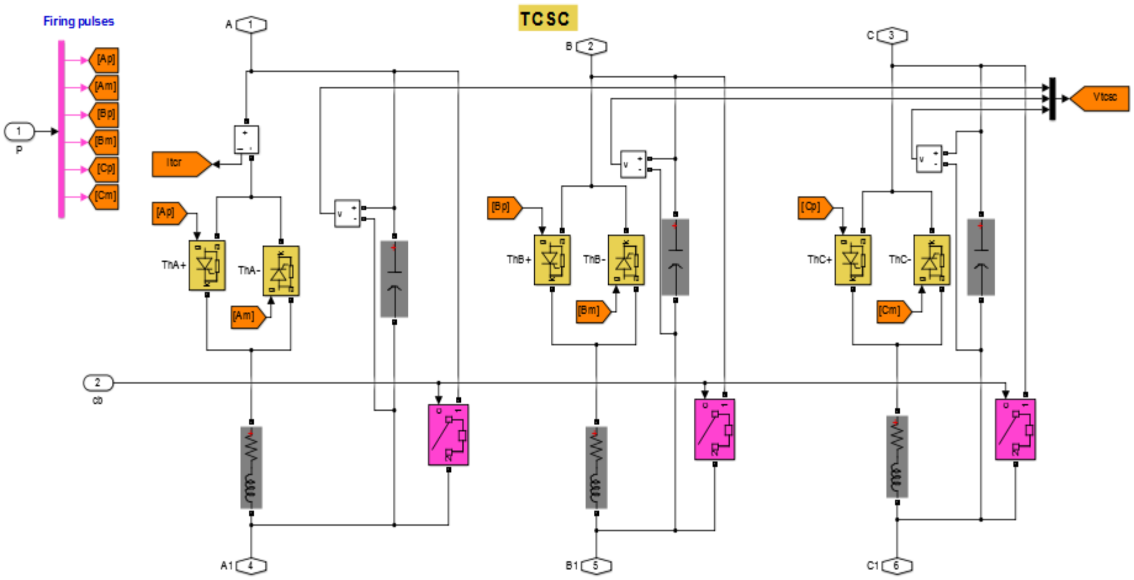

Figure B-4 MATLAB model of internal structure of TCSC

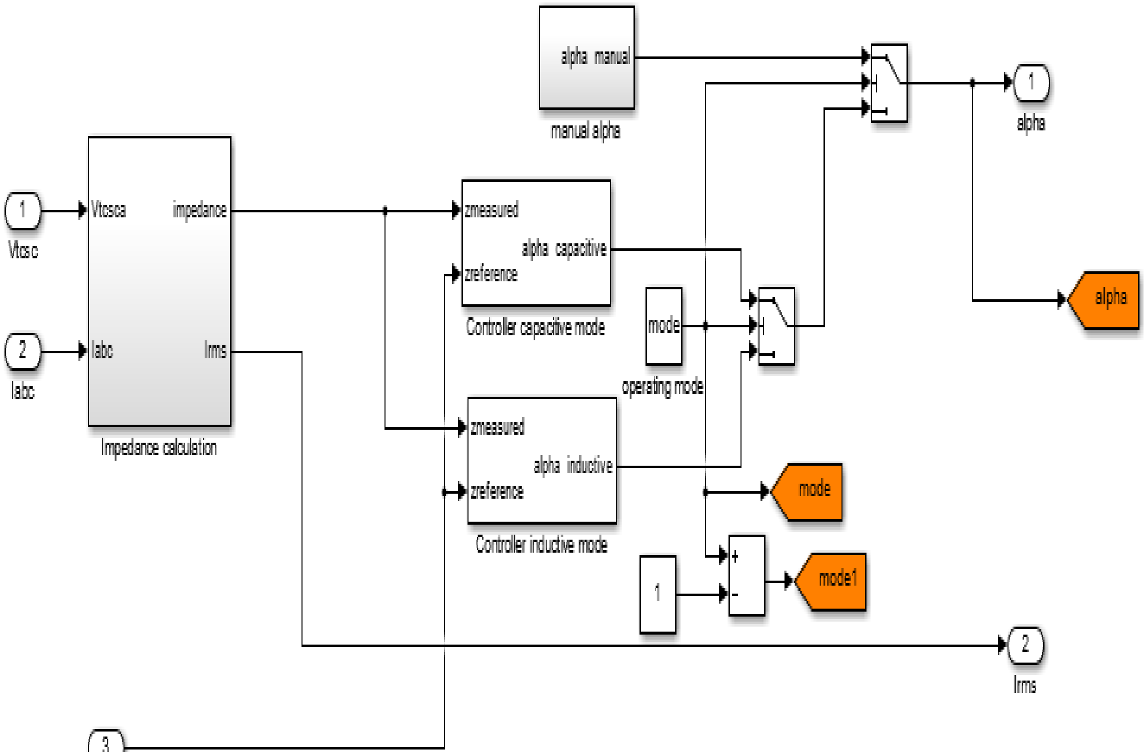

Fig.B-5 The impedance calculation block in the control unit