

Chapter One

Introduction

1.1 Background

The demand for more power with better quality and higher reliability at lower cost face power transmission and distribution systems nowadays, so the transmission networks have to operate at high transmission levels. Power engineers confront some major operating problems such as transient stability, damping of oscillations and voltage regulation. The generator excitation controllers can assess the rotor angle stability and voltage regulation but with only excitation control, the system stability may not be maintained if a large fault occurs close to the generator terminal, or simultaneous transient stability and voltage regulation enhancement may be difficult to achieve. FACTS family controllers such as static synchronous compensator (STATCOM) has proved that it supply reactive power compensation to power systems which provide voltage support, increase transient stability and improve damping of power system [1].

FACTS is a system which incorporates power electronic-based technology which means solid state devices, in order to control bulk power flows in transmission system. Static control equipment are used with FACTS to accommodate changes in the electric transmission systems or operating conditions while maintaining sufficient steady-state and transient margins. In other words, it integrates the modern power electronics technology with traditional power system technology.

The main values that FACTS technology can bring are:

- Flexibility of power flow control enhancement, in order to keep power flow over desired routes, avoid over-loading or under-loading certain transmission lines, reduce undesirable VAR (Voltage-ampere reactive) flow and dynamic voltage control
- Increase power transfer capability of the transmission system to its limit.
- Improve voltage and transient stability.

The above are vital features for the power system stability. FACTS system consist of a single or multiple thyristor-based controllers which can be applied individually or simultaneously to control the parameters of transmission networks, such as, series impedance, shunt impedance, phase angle to achieve the above [2], [3].

1.2 FACTS Controllers Types

The FACTS controllers are classified as follows:

- Thyristor controlled based FACTS controllers such as:
 - Static var compensator (SVC)
 - Thyristor controlled series compensator (TCSC)
- VSC based FACTS controllers such as:
 - Static synchronous compensator (STATCOM)
 - Static synchronous series compensator (SSSC)
 - Unified power flow controller (UPFC) [4], [5]

The main drawback of thyristor controlled based FACTS controllers is the resonance phenomena occurs but VSC based FACTS controllers are free from this phenomena. So that the overall performance of VSC based FACTS controllers are better than of that the thyristor controlled based FACTS controllers [6].

1.3 Classifications of FACTS Devices in Terms of Connection

FACTS in terms of connection can be classified into four types:

- Series FACTS controllers
- Shunt FACTS controllers
- Combined series-series FACTS controllers
- Combined series-shunt FACTS controllers [7]

1.3.1 Series FACTS Controllers

The series FACTS controllers could be a variable impedance such as capacitor, reactor or a power electronic based variable source. Typical series compensators use capacitors in order to reduce the equivalent reactance of a power line at rated frequency,

according to that the voltage increase at the load terminals which in principle injects voltage in series with the line, the series controllers either supplies or consumes variable reactive power because the voltage is in phase quadrature with the line current. other phase relationship will result in handling of real power also. There are various important series compensators such as static synchronous series compensator (SSSC), Thyristor-controlled series compensation (TCSC) [7].

1.3.2 Shunt FACTS Controllers

The shunt controllers could be variable impedance like capacitor, reactor or power electronic based variable source, which is shunt connected to the line to inject variable current. Because of the current is injected in phase quadrature with the line voltage, the shunt controllers solely supplies or consumes variable reactive power. Any other phase relationship will involve handling of real power as well. The important shunt compensators are static var compensator (SVC) static synchronous compensator (STATCOM) [7].

1.3.3 Combined Series-Series FACTS Controllers

These controllers are the combination of separate series FACTS controllers, which are controlled in a co-ordinated manner in a multiline transmission system. The configuration of combined series-series FACTS controllers provide independent series reactive power compensation for each line but also transfers real power among the lines via power link. The presence of power link between series controllers names this configuration as unified series-series controller [7].

1.3.4 Combined Series-Shunt FACTS Controllers

These are combination of separate shunt and series controller, which are controlled in a co-ordinate manner or a unified power flow controller with series and shunt elements. When the shunt and series FACTS controllers are unified, there can be a real power exchange between the series and shunt controllers via power link [7].

1.4 Stability Enhancement

The safety and instability concern of power systems is the main factor in limiting the delivery capacity of the power grids. For the existing power grids, there is a big margin between its realistic transfer capacity capped its stability limit and its maximum capacity. Therefore, enhancing the stability of power grids is one way for increasing the capacity of transmission lines [2]. Power systems have to deal with important control problems constantly. One is to maintain its transient stability which means maintain the synchronization between generators following a severe disturbance. The other one is maintain steady voltage under normal operating and disturbed conditions. Effective controllers for enhancing the stability need to be implemented to actively damp the post-fault power and voltage oscillations. The increase in the loading of transmission lines sometimes can also lead to voltage collapse due to the shortage of reactive power delivered. The appropriate control of reactive power flow in the grid is thus critical. The stability of power grids can be improved by changing the power angle or voltage level or reactive compensation [2].

1.5 Motivation

The transients can be initiated in the power system due to faults or unbalance between the generation and load that causes the rotors of synchronous machines to swing because net accelerating torques are exerted on these rotors, eventually the machine may loss the synchronism. To improve the transient stability various FACTS devices are used. STATCOM is most promising device among the entire FACTS devices. STATCOM can enhance the real and reactive power capacity of the system.

1.6 Thesis Objective

The objectives of the thesis are :

- To study the basic operation of STATCOM.
- Modeling of STATCOM in MATLAB/SIMULINK environment and PSAT software.
- Focus on the control strategy of STATCOM.

- To investigate STATCOM ability in enhancing the transient stability by analysis the system behavior for disturbance conditions without implementation of STATCOM and with implementation of STATCOM.

1.7 Thesis Organization

Chapter One: This chapter discusses background about power system stability and FACTS, FACTS controllers types, classifications of FACTS devices in terms of connections, motivation and thesis objectives.

Chapter Two: Describes static synchronous compensator, its operating principle and its applications. This chapter contains comparison between SVC and STATCOM and transient stability enhancement.

Chapter Three: This chapter presents the mathematical modeling of synchronous machine, excitation system, hydro turbine-governor, STATCOM, STATCOM control system and space vector PWM also this chapter describes STATCOM transient stability model.

Chapter Four: Presents firstly the simulation results and discussions of two machine system under 3- phase fault and the system installed without and with STATCOM, secondly two machine system with step changing load and the system implemented with and without STATCOM. This chapter also contains simulation results and discussions of multi-machine system under 3-phase fault with and without STATCOM.

Chapter Five: Presents conclusion and suggestions for future work.

Chapter Two

Literature Review

2.1 General Introduction

Modern power systems consist of several generating plants and very high number of consumers, employ a variety of transmission and distribution voltages. Large geographic territories have been covered with a large number of interconnection and distribution points through which the electric energy is transmitted or delivered. Power system operation became very complex and less secure due to continuous load growth and higher power transfer in a largely interconnected network. In the past the desired voltage levels and the system stability could be maintained by fixed compensation, line reconfiguration and better protection. Addition of new transmission lines may be impossible solution due to environmental and other considerations [8]. A new approaches to power system operation and control has to be developed for overload relief, an efficient and reliable operation. Power engineers facing problems such as supporting dynamic disturbances like transmission lines switching, loss of generation, shortcircuits and load rejection, needs the reactive control to be fast enough to maintain the desired voltage levels and system stability, according to these challenges it is very essential to seek solutions to operate the system in more flexible and controllable manner. The experiences over the past decades proved that the process to permit site and construct new transmission lines has become very difficult, expensive, time-consuming and controversial. FACTS technologies has been introduced to replace traditional solutions such as new transmission line construction [8].

SVC (static var compensator) and STATCOM are the most important FACTS devices because of their broad applications in electric utility industry, the STATCOM has ability to generate more reactive power than SVC. STATCOM also named ASVG (Advanced Static Var Generator) is very promising to be the key technologies in future power system [8].

2.2 Static Synchronous Compensator

The Static Synchronous Compensator (STATCOM) is one of the shunt FACTS devices which has ability to generate and/ or absorb reactive power so as to maintain control of specific parameters of electric power system. The operation characteristics of STATCOM is similar to a rotating synchronous compensator without the mechanical inertia [9]. Because STATCOM uses solid state power switching devices it provides rapid controllability of three phase voltages in magnitude and phase angle. STATCOM consists of a three-phase GTO/ IGBT voltage source converter (VSC), step down transformer and a DC capacitor. The reactive power exchange between the STATCOM and the power system occur due to AC voltage difference across the leakage reactance. According to this reactive power exchange the AC voltage at the bus bar can be regulated to improve the voltage profile of the power system. STATCOM duties may be divided into two parts, the primary duty is voltage regulation and the secondary duty is damping function for enhancing power oscillation stability [9], [10].

2.2.1 Operating Principle of STATCOM

STATCOM consists of a coupling transformer, a VSC and a dc energy storage device. STATCOM has ability to exchange reactive power with the transmission line due to its small energy storage device that means small dc capacitor. This dc capacitor can be replaced with dc storage battery or other dc voltage source. The controller can exchange real and reactive power with the transmission system, extending its region of operation from two to four quadrants [11]. A functional model of a STATCOM is shown in Figure 2.1

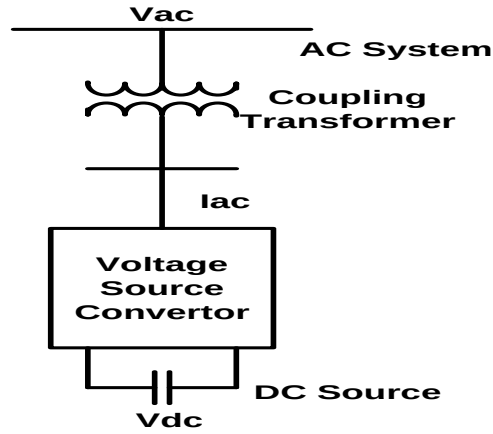


Figure 2.1 Functional Model of STATCOM

The relationship between fundamental component of the converter ac output voltage and voltage across dc capacitor is given as :

$$V_{out} = kV_{dc} \dots \dots \dots (2.1)$$

Where k is co-efficient which depends upon the converter configuration, number of switching pulses and the converter controls. V_{out} can be controlled by varying the dc voltage across capacitor which can be achieved by changing the phase angle α of the operation of the converter switches relative to the phase of the ac system bus voltage. The flow of reactive power could be from coupling transformer to the system or from system to the coupling transformer this depends upon the difference between the converter output voltage and the ac system bus voltage. When the real power flowing into the converter, the converter losses occurred because of switching and charges the dc capacitor to a satisfactory dc voltage level [11], [12]. In steady state during each switching cycle the capacitor is charged or discharged, the average capacitor voltage remains constant. If that were not the case, the real power will flow into or out of the converter, and in each cycle the capacitor would gain or lose charge. All of the power from the ac system is used to replenish the losses because of switching in steady state. The size of dc capacitor and the real power losses due to switching indicate STATCOM ability to absorb/ supply real power. If the dc capacitor and the losses are relatively small implies that the amount of real power transfer is also relatively small which indicates that STATCOM'S output ac current I_{ac} , has to be approximately 90° with respect to ac

system voltage at its line terminals. The reactive power generation/ absorption of the STATCOM could be controlled by varying the amplitude of the converter three phase output voltage V_{out} . The ac current I_{ac} flows through the transformer reactance from the converter to the ac system generating reactive power if the amplitude of the converter output voltage V_{out} is greater than the amplitude of the ac system bus voltage V_{ac} . If the converter losses are neglected and the amplitude of the ac system equal to the converter output voltage the current will not flow in/ out of the converter, hence there will be no reactive power generation/ absorption. The ac current magnitude can be calculated using the following equation :

$$I_{ac} = \frac{V_{out}-V_{ac}}{X} \dots\dots\dots(2.2)$$

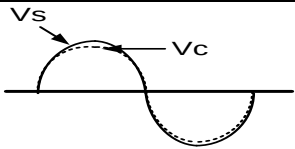
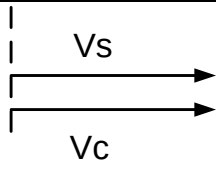
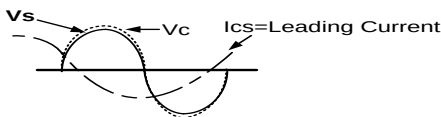
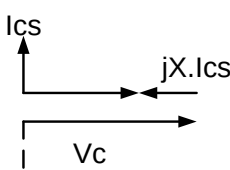
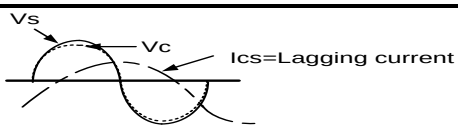
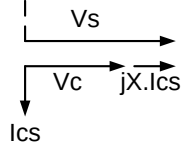
Assuming that the ac current flows from the converter to the ac system. V_{out} and V_{ac} are the magnitudes of the converter output voltage and ac system voltage respectively, while X represents the coupling transformer leakage reactance. The reactive power exchange can be expressed as follows [11], [12] :

$$Q = \frac{V_{out}^2 - V_{out}V_{ac} \cos \alpha}{X} \dots\dots\dots(2.3)$$

2.2.2 Operating Modes

STATCOM has three operating mode no load mode, capacitive operation mode and inductive operation mode , the operation mode depends on the system needs for reactive power, if the system needs negative reactive power then STATCOM works in the capacitive mode but if the system needs positive reactive power then the STATCOM works in inductive mode. When the system needs no compensation the STATCOM works in no load mode. The table 2.1 below shows waveform and phasor of each mode [13].

Table 2.1 Operating modes of STATCOM

Mode	Waveform	Phasor
No load Mode	 (a) $V_c = V_s$	
Capacitive operation mode	 (b) $V_c > V_s$	
Inductive operation mode	 (c) $V_c < V_s$	

2.2.3 Voltage Source Converter (VSC)

Three phases VSC contains six switches as shown in Figure 2.2. The switches (S1 and S4, S3 and S6, or S5 and S2) are connected to the same leg of the inverter. These switches can't be switched on simultaneously because this would result in a short circuit across the dc link voltage supply. To avoid undefined states in the VSC, the switches of any leg of the inverter cannot be switched off simultaneously. If six switches are used we can have eight switching topology. Out of eight valid states, two of them produce zero ac line voltages in this case the ac line currents freewheel through either the upper or lower components [14]. The selection of the states in order to generate required waveform is done by the modulating technique.

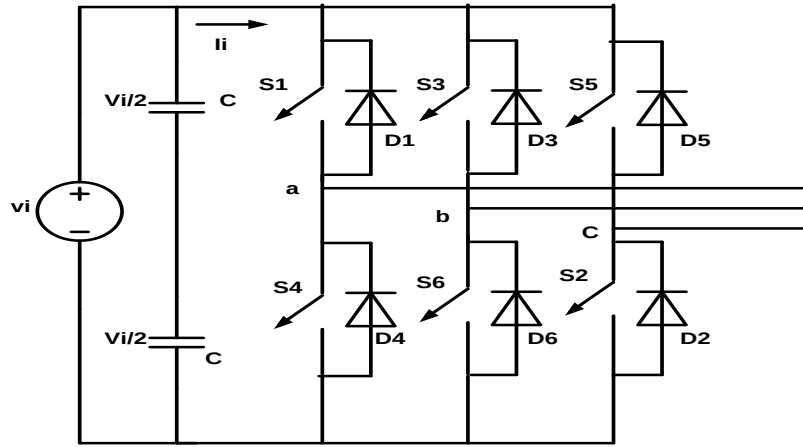


Figure 2.2 Voltage Source Converter

The switches of VSC may be GTOs, IGBTs, IGCTs, or other self commutating switches with an antiparallel-connected diode, which will operates with a unidirectional voltage-blocking capability and a bidirectional current flow [14].

2.2.4 STATCOM V-I Characteristics

Modes of the STATCOM operation :

- Voltage regulation mode
- VAR control mode

When the STATCOM is worked in voltage regulation mode, it implements the V-I characteristic as shown in Figure 2.3. The V-I characteristic is depicted by the following equation:

$$V = V_{ref} + X_s I \dots \dots \dots (2.4)$$

Where:

V = Positive sequence voltage (pu)

I = Reactive current (pu/ P_{nom})

($I > 0$ indicates an inductive current and $I < 0$ indicates capacitive current)

X_s = Slope (pu/ P_{nom} : usually between 1% and 5%)

P_{nom} = Converter rating in MVA [15].

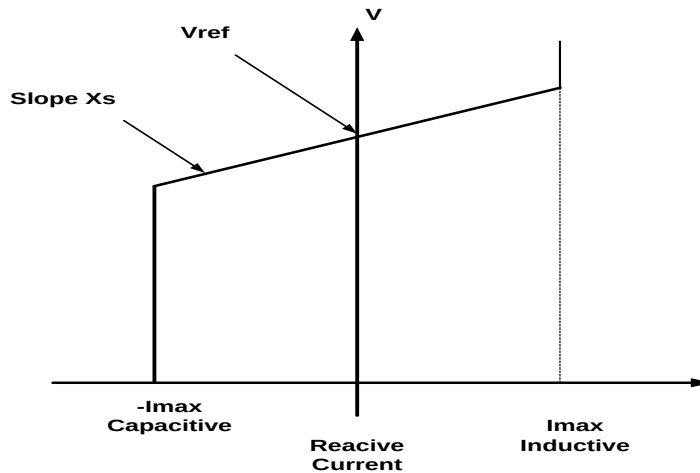


Figure 2.3 V-I characteristics of STATCOM

2.3 STATCOM Applications

STATCOM has various applications in power systems, it is used for transient stability enhancement, voltage regulation, power quality and transmission system but its application in the transmission system is most popular for the purpose of reactive power compensation and increase power transmission limits

2.3.1 Transmission Applications

Several prototype STATCOM have been used in the transmission network, also several smaller STATCOM installations have been used, particularly in japan, to reduce flicker caused by electric arc melting furnace. STATCOMs advantages over SVCs such as equality of lagging and leading outputs, faster response time, possible active harmonic filtering capability, and smaller footprint. STATCOM of ± 80 Mvar was put in service in japan in 1991. The main converter circuit configuration is given in Figure 2.4. Eight of voltage-sourced converters each of 10 MVA rating, connected to a main STATCOM transformer via eight converter

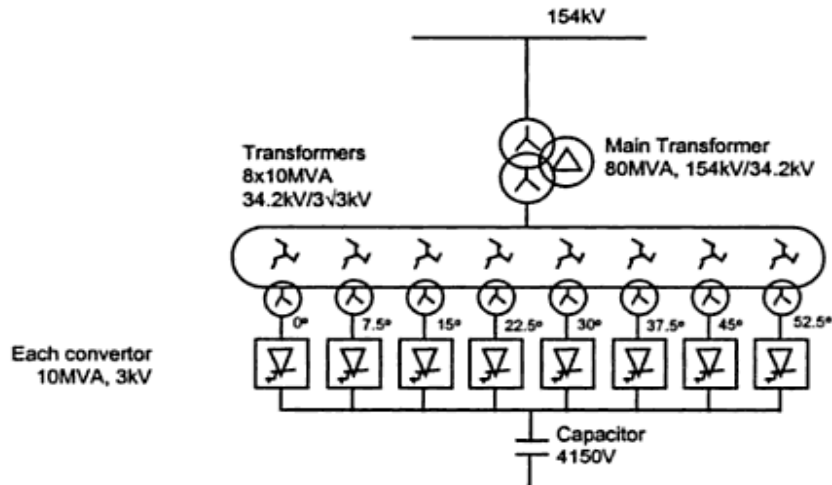


Figure 2.4 ± 80 Mvar STATCOM

The control system consists of power system voltage control, power oscillation damping and constant reactive power output control. The width of the rectangular output voltage of each converter can be varied via the control system to achieve voltage magnitude control and to ensure low losses. In order to reduce the effects of dc magnetization, decrease magnetic impedance the effects of dc magnetization, decrease magnetic impedance, and improve the uniformity of voltage sharing between windings a gapped-core design is used for the eight phase-displacement transformers. This is especially important when the STATCOM is energized from the power system during start up sequences or following system faults. Initially the converter start-up system used a relatively large, separate, “start-up converter” to supply dc voltage to the STATCOM main converter. But the drawback of this method that is slow. Now a new system allows the STATCOM converter to start immediately after the energization of the STATCOM transformer and the eight converter transformers from the power system.

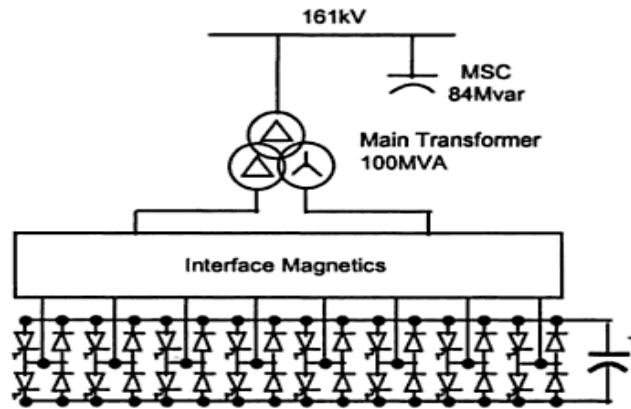


Figure 2.5 Illustrate the main converter circuit configuration of ± 100 MVA prototype STATCOM.

Eight 12.5 MVA voltage-sourced converters are connected through a main STATCOM transformer and through “interface magnetic” to substation 161 kV, the STATCOM transformer include phase shifting transformers which give quasi 48-pulse operation as shown in Figure 2.5. The full reactive power output range of the STATCOM and an associated MSC of 84 Mvar are used to regulate the 161 kV busbar voltage and minimize transformer tap changer operation on the 500kV/161kV transformer feeding the substation [16]. A part from the normal voltage control on the 161 kV busbar the STATCOM also helps to prevent voltage collapse under system contingency conditions such as the loss of a 500kV circuit confidence in the STATCOM principle has now grown sufficiently for some utilities to consider them for normal commercial service. In 1996, the National Grid Company plc of England and Wales sought relocatable dynamic reactive compensation equipment for its 400kV transmission network, capable of generating 0 to 225Mvar at 0.95 p.u. system voltage. With a particular reference to the inclusion of a STATCOM of 150Mvar range. The design adopted includes a ± 75 Mvar TSC and 23Mvar harmonic filter to provide a full controlled range of output +225 to -52 Mvar, Figure 2.6

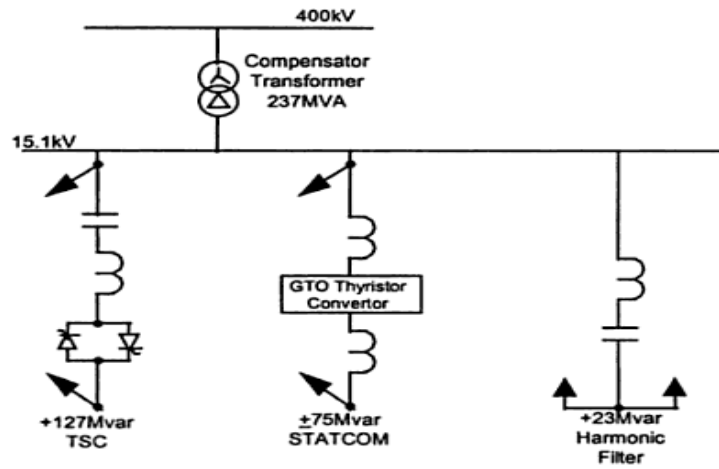


Figure 2.6 +225/-52 Mvar SVC including ± 75 Mvar STATCOM

This STATCOM design is required to meet stringent harmonic emission levels and immunity to existing and future prospective harmonic levels. It uses multi-level converters in a chain circuit configuration. The control system incorporates voltage control, reactive setpoint regulation, and a co-ordinating control for the STATCOM and the associated TSC. Provision is also made to include power oscillation damping control in the future. All controls and power electronics equipment are housed in weatherproof, transportable GRP (glass reinforced plastic). Cabins and the outdoor components are grouped together on frameworks to satisfy the requirement for easy relocation to another substation when this is required [16].

2.3.2 Power System Stability Applications

The STATCOM has the following applications in controlling power system dynamics

- Damping of power system oscillations
- Damping of subsynchronous oscillations
- Balanced loading of individual phases
- Reactive compensation of AC-DC converters and HVDC links
- Improvement of transient stability margin
- Improvement of steady-state power transfer capacity
- Reduction of temporary over-voltages
- Effective voltages regulation and control

- Reduction of rapid voltages fluctuations (flicker control) [17].

2.4 Comparison Between SVC and STATCOM

The development of the flexible alternating current transmission system (FACTS) is a result of the recent advances in power electronics. SVC (Static Var Compensator) and STATCOM (Static Synchronous Compensator) are two types of FACTS device which can be used for voltage control and reactive power compensation. SVC is a shunt connected static var generator/Load whose output can be adjusted to exchange capacitive or inductive current in order to maintain or control specific power system variables. STATCOM is a voltage-source converter based device, which converts a DC input voltage into an AC output voltage for active and reactive compensation needs of the system. Due to widespread using of FACTS devices and smart grid, SVC and STATCOM are paid more and more attention. SVC and STATCOM are used in transmission system in power grid as reactive compensation equipment. Requirements for transmission system are as follows:

- Voltage supporting
- Improving the transient stability and transmission limit
- Damping low frequency oscillation

STATCOM is much better than SVC in output characteristics, power loss, response time and harmonics, even though STATCOM is costly and more complicated [18].

2.4.1 V-I and V-Q Characteristics

The STATCOM is consisting of an alternating voltage source behind a coupling reactance, with the corresponding V-I and V-Q characteristics shown in figures 2.7(a) and 2.8(a), respectively. This illustrate the ability of STATCOM operation over its full output current range even at very low (theoretically zero), typically about 0.2 p.u system voltage levels. In other words, the maximum capacitive or inductive output current of the STATCOM can be maintained indepently of the a.c system voltage which is changed linearly with the maximum var generation or absorption. The SVC is composed of

thyristor-switched capacitors and reactors, becomes a fixed capacitive admittance at full output.

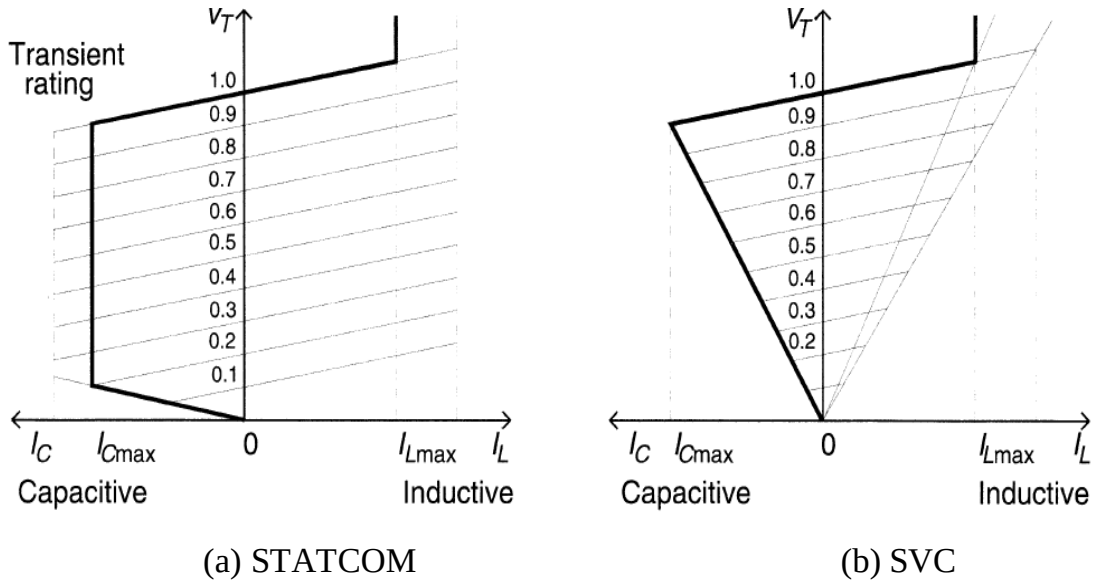


Figure 2.7 V-I characteristic of (a) the STATCOM and (b) the SVC

Accordingly the maximum compensating current decreases linearly with ac system voltage and the maximum var output decreases with the square of this voltage as shown in figures 2.7(b) and 2.8(b), respectively. Therefore STATCOM is better than SVC in voltage support at large system disturbances during which the voltage excursions exceed the linear operating range of the compensator. Because of the STATCOM capable of providing maximum compensating current at reduced system voltage, it can be used in a variety of applications the same dynamic compensation as an SVC of considerably higher rating. As Figures 2.7 (a) and 2.8 (a) illustrate. Independently from the power semi-conductors used, the STATCOM may have an increased transient rating in both the inductive

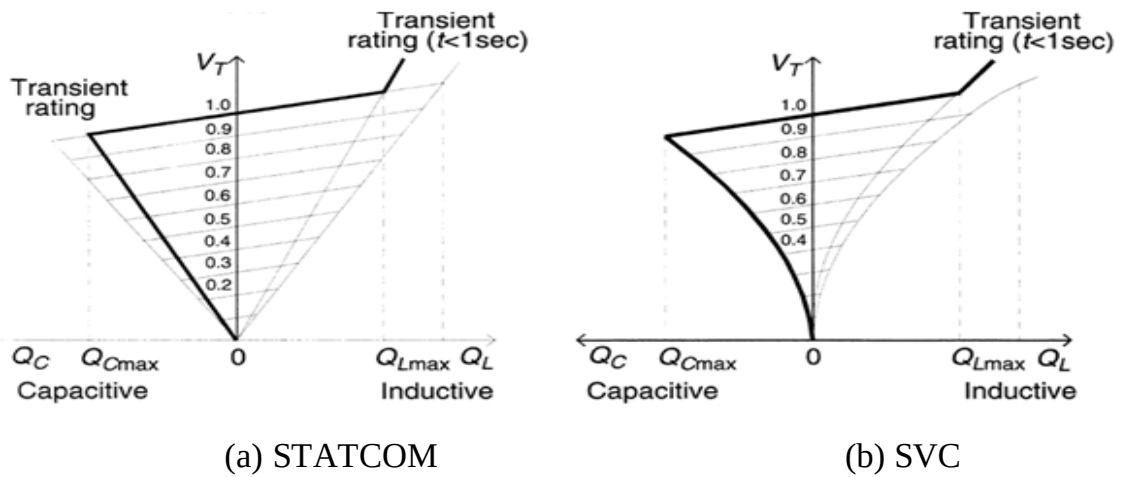


Figure 2.8 V-Q characteristic of (a) the STATCOM and (b) the SVC

and capacitive operating regions. (The SVC has no means to increase transiently the var generation since the maximum capacitive current it can draw is strictly determined by the size of the capacitor and the magnitude of the system voltage) The maximum attainable transient overcurrent of the STATCOM in the capacitive region is determined by the maximum current turn-off capability of the power semiconductors (e.g., GTO thyristors) employed. In the inductive operating region the power semiconductors of an elementary converter, switched at the fundamental frequency, are naturally commutated. This means that the transient current rating of the STATCOM in the inductive range is, theoretically, limited only by the maximum permissible GTO junction temperature, which would in principle allow the realization of a higher transient rating in this range than that attainable in the capacitive range. However, it should be pointed out that this possibility would generally not exist if the converter poles were operated to produce a pulse-width modulated waveform, when the current conduction between the upper and lower valves is transferred several times during each fundamental half cycle. Even with non-PWM converters, abnormal operating conditions should be carefully considered in the implementation of transient ratings above the peak turn-off current capability of the semiconductors employed, because if an expected natural commutation would be missed for any reason, converter failure requiring a forced shutdown would likely occur [19]

2.4.2 Transient Stability Enhancement

The ability of the STATCOM to maintain full capacitive output current at low system voltage also makes it more effective than the SVC in improving the transient (first swing) stability. The effectiveness of the STATCOM in increasing the transmittable power is illustrated in Figure 2.9 (a), where the transmitted power P is shown

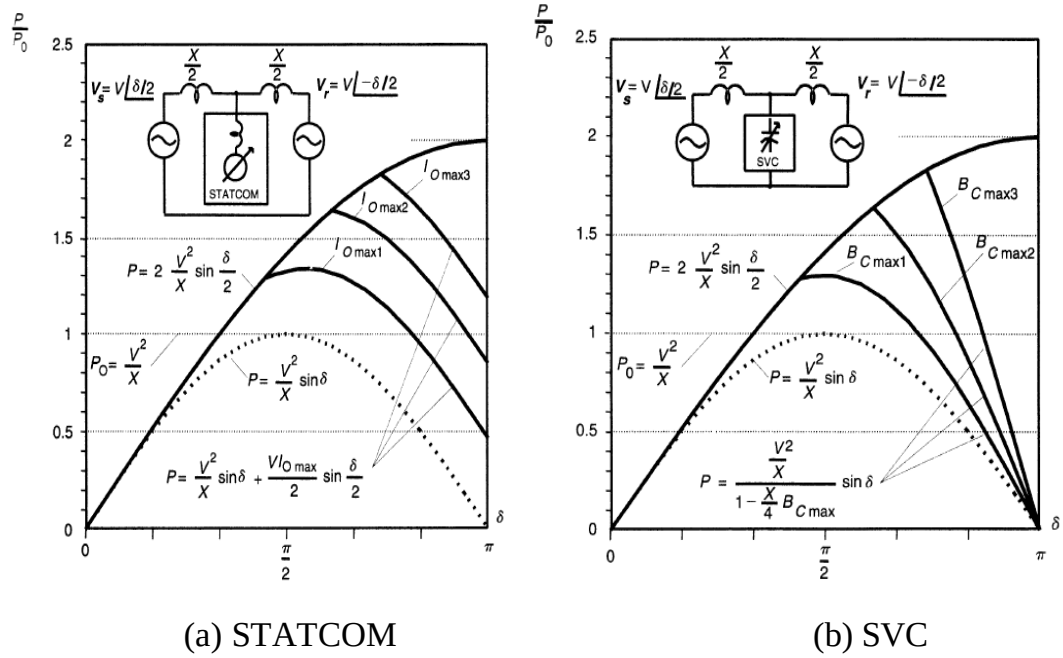


Figure 2.9 Transmitted power versus transmission angle of a two-machine system with a (a) midpoint STATCOM and (b) a midpoint SVC obtained with different var ratings.

against the transmission angle δ for the usual two-machine model at various capacitive ratings defined by the maximum capacitive output current $I_{C\max}$. For comparison, an equivalent P versus δ relationship is shown for an SVC in Figure 2.9 (b). It can be observed that the STATCOM, just like the SVC, behaves like an ideal midpoint shunt compensator with P versus δ relationship as defined by $P = (2V^2 / X) \sin(\delta/2)$ until the maximum capacitive output current $I_{C\max}$ is reached. From this point, the STATCOM keeps providing this maximum capacitive output current (instead of a fixed capacitive admittance like the SVC), independent of the further increasing angle δ and the consequent variation of the midpoint voltage. As a result, the sharp decrease of transmitted power P in the $\pi/2 < \delta < \pi$ region, characterizing the power transmission

of an SVC supported system, is avoided and the obtainable $\int P d\delta$ area representing the improvement in stability margin is significantly increased. The increase in stability margin obtainable with a STATCOM over a conventional thyristor-controlled SVC of identical rating is clearly illustrated in Figures 2.10 (a) and (b) [19]. The simple two-machine system, is compensated at the midpoint by a STATCOM and an SVC of the same var rating. For the sake of clarity, it is assumed that the system transmitting steady-state electric power P_1 at angle δ_1 , is subjected to a fault for a period of time during which P_1 becomes zero. During the fault, the sending-end machine accelerates (due to the constant mechanical input power), absorbing the kinetic energy represented by the shaded area below the constant P_1 line, and increasing δ_1 to δ_c ($\delta_c > \delta_1$). Thus, when the original system is restored after fault clearing, the transmitted power becomes much higher than P_1 due to the larger transmission angle δ_c . As a result, the sending-end machine starts to decelerate, but δ increases further until the machine loses all the kinetic energy it gained during the fault. The recovered kinetic energy is represented by the shaded area between the P versus δ curve and the constant power line P_1 . The remaining unshaded area below the P versus δ curve and above the constant power line P_1 provides the transient stability margin. As can be observed, the transient stability margin obtained with the STATCOM, due to the better support of the midpoint voltage, is significantly greater than that attainable with the SVC of identical var rating.

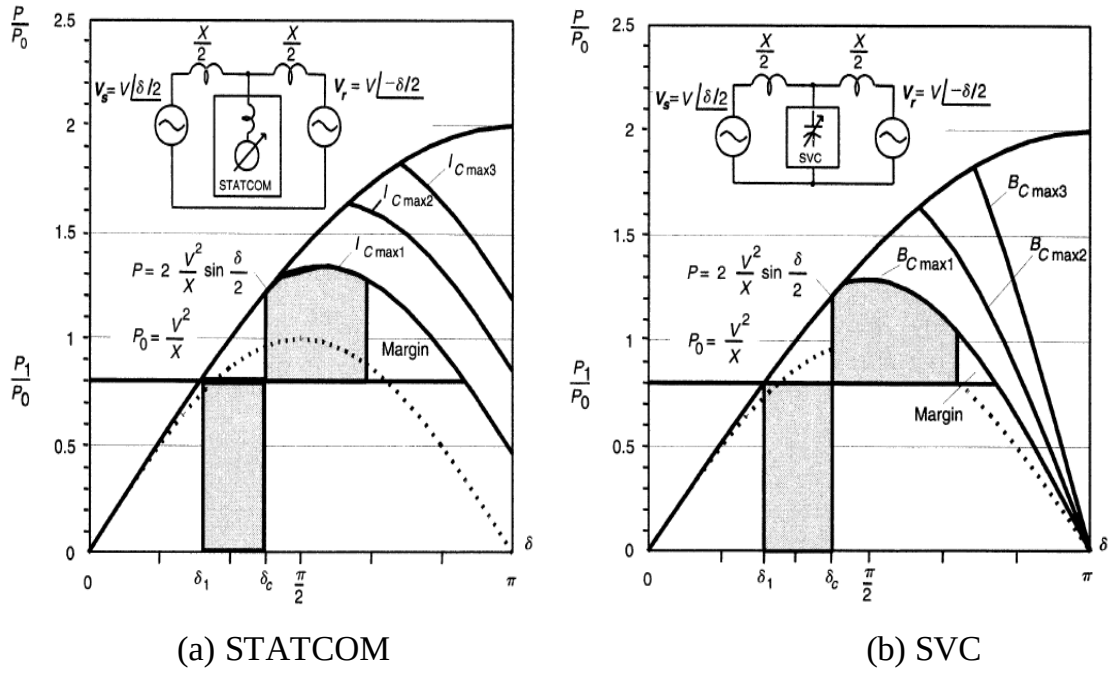


Figure 2.10 Improvement of transient stability obtained with (a) a midpoint STATCOM and (b) a midpoint SVC of a given var rating.

This of course means that the transmittable power can be increased if the shunt compensation is provided by a STATCOM rather than by an SVC, or, for the same stability margin, the rating of the STATCOM can be decreased below that of the SVC [19].

2.5 Summary

In this chapter static synchronous compensator, its operating principle, voltage source converter and STATCOM V-I characteristics in the case of voltage regulation mode and var control mode has been discussed, STATCOM applications in the transmission system and power system stability also has been discussed. The comparison between STATCOM and SVC in terms of V-I and V-Q characteristics and transient stability enhancement and the reasons that STATCOM is preferred in transient stability enhancement over SVC has been presented.

Chapter Three

Mathematical Model

3.1 General

STATCOM (Static Synchronous Compensator) is one of the most important flexible AC transmission systems (FACTS) devices because of its ability to regulate voltages in transmission lines, to improve transient stability and to compensate variable reactive power. These devices are also interesting at the distribution level, where fast compensation of large, fluctuating industrial loads (Such as electric arc furnaces and rolling mills) can be achieved, substantially improving upon the performance achievable with conventional thyristor-based converters. For low-medium power applications at the distribution level, such devices (Sometimes called D-Statcom (Distribution Statcom) or also active filters) are able also to perform compensation for the load current harmonics produced by distorting load, to comply with harmonic standards.

In this chapter power system components will be modeled such as synchronous machine, excitation system, Hydro turbine-Governor and STATCOM, also STATCOM control system model, Space Vector PWM model and STATCOM Transient Stability Model will be discussed [20].

3.2 Power System Modeling

The nonlinear differential equations of the system under study are derived by developing individually the mathematical models which represent the various components of the system, namely the synchronous generator, the excitation system, hydro turbine-governor system, STATCOM and its control system . Knowing the mutual interaction among these models, the whole system differential equations can be formed [21].

3.2.1 Modeling of Synchronous Machine

The mathematical model of synchronous machine can be obtained by using Park's transformation and a set of first order differential equations may be written as follows

Flux linkage model:

$$p\delta = \omega \dots \dots \dots (3.1)$$

$$p\omega = \frac{\omega_0}{2H} [T_m - T_e] \dots \dots \dots (3.2)$$

$$p\psi_F = \omega_0 [V_F - i_F R_F] \dots \dots \dots (3.3)$$

$$p\psi_d = \omega_0 [V_d + i_d R_d + \psi_q] + \psi_q \omega \dots \dots \dots (3.4)$$

$$p\psi_D = -\omega_0 R_D i_D \dots \dots \dots (3.5)$$

$$p\psi_q = \omega_0 [V_q + i_q R_q - \psi_d] - \psi_d \omega \dots \dots \dots (3.6)$$

$$p\psi_Q = -\omega_0 R_Q i_Q \dots \dots \dots (3.7)$$

$$T_e = \psi_d i_q - \psi_q i_d \dots \dots \dots (3.8)$$

Where T_e stand for electrical torque, T_m for mechanical torque V_F for field voltage V_d, V_q for direct and quadrature axis voltage respectively, R_F for field winding resistance R_A for direct and quadrature axis winding resistance, R_D, R_Q for direct and quadrature axis damper winding resistance respectively. ψ_F for field winding flux, ψ_d, ψ_q for direct and quadrature axis flux respectively ψ_D, ψ_Q for direct and quadrature axis damper winding flux respectively [22].

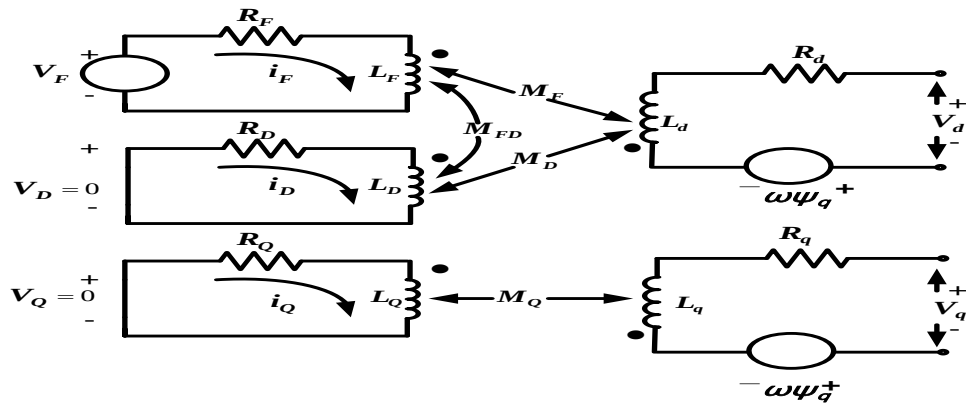


Figure 3.1 Schematic diagram of a synchronous machine

Voltage equations of a synchronous machine in d-q axis with the following forms:

$$\begin{bmatrix} V_F \\ V_D \\ V_Q \\ V_d \\ V_q \end{bmatrix} = \begin{bmatrix} R_F & 0 & 0 & 0 & 0 \\ 0 & R_D & 0 & 0 & 0 \\ 0 & 0 & R_Q & 0 & 0 \\ 0 & 0 & 0 & R_d & 0 \\ 0 & 0 & 0 & 0 & R_q \end{bmatrix} \begin{bmatrix} i_F \\ i_D \\ i_Q \\ i_d \\ i_q \end{bmatrix} + \begin{bmatrix} L_F & M_{FD} & 0 & M_F & 0 \\ M_{FD} & L_D & 0 & M_D & 0 \\ 0 & 0 & L_Q & 0 & M_Q \\ M_F & M_D & 0 & L_d & 0 \\ 0 & 0 & M_Q & 0 & L_q \end{bmatrix} \begin{bmatrix} pi_F \\ pi_D \\ pi_Q \\ pi_d \\ pi_q \end{bmatrix} +$$

$$\omega \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & M_Q & 0 & L_q \\ -M_F & -M_D & 0 & -L_d & 0 \end{bmatrix} \begin{bmatrix} i_F \\ i_D \\ i_Q \\ i_d \\ i_q \end{bmatrix} \dots\dots\dots(3.9)$$

The swing equations are:

$$p\delta = \omega \dots\dots\dots(3.10)$$

$$p\omega = \frac{\omega_0}{2H} [T_m - T_e] \dots\dots\dots(3.11)$$

3.2.2 Excitation System

The block diagram representation of the excitation system is shown in Figure 3.2 below:

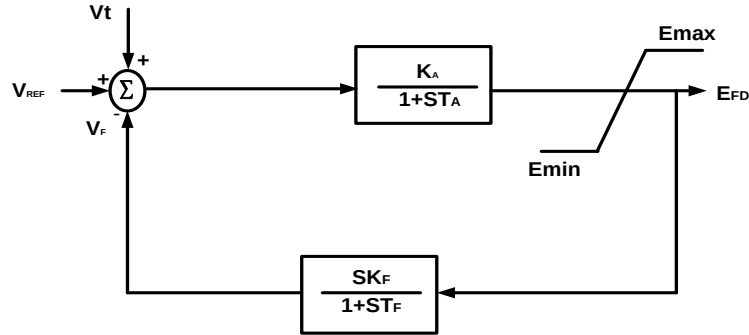


Figure 3.2 Block diagram of the excitation system.

The main regulator transfer function is represented as a gain K_A and a time constant T_A , following this, the maximum and minimum limits of the regulator are imposed so that large input error signals cannot produce a regulator output exceeds practical limits.

The state-space equation of the excitation system can be derived from its block diagram and is given by [23] :

$$\begin{bmatrix} pE_{FD} \\ pV_F \end{bmatrix} = \begin{bmatrix} \frac{-1}{T_A} & \frac{-K_A}{T_A} \\ \frac{-K_F}{T_A T_F} & \frac{-(K_A K_F + T_A)}{T_A T_F} \end{bmatrix} \begin{bmatrix} E_{FD} \\ V_F \end{bmatrix} + \begin{bmatrix} \frac{K_A}{T_A} & \frac{-K_A}{T_A} \\ \frac{K_A K_F}{T_A T_F} & \frac{-K_A K_F}{T_A T_F} \end{bmatrix} \begin{bmatrix} V_{REF} \\ V_t \end{bmatrix} \dots\dots\dots(3.12)$$

3.2.3 Hydro Turbine-Governor Model

The block diagram representation of the hydro turbine-governor is shown in Figure 3.3 below [23] :

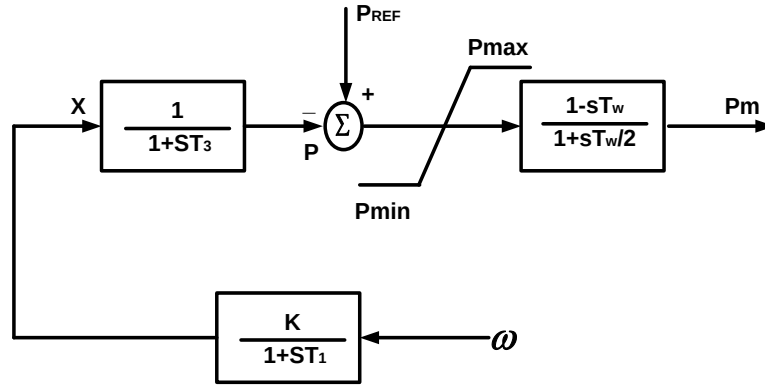


Figure 3.3 Block diagram of Hydro Turbine-Governor system

The state space of the above block diagram can derived as follow:

$$\begin{bmatrix} pX \\ pP \\ pY \end{bmatrix} = \begin{bmatrix} \frac{-1}{T_1} & 0 & 0 \\ \frac{1}{T_3} & \frac{-1}{T_3} & 0 \\ 0 & \frac{-6}{T_w} & \frac{-2}{T_w} \end{bmatrix} \begin{bmatrix} X \\ P \\ Y \end{bmatrix} + \begin{bmatrix} 0 & \frac{K}{T_1} \\ 0 & 0 \\ \frac{6}{T_w} & 0 \end{bmatrix} \begin{bmatrix} P_{REF} \\ \omega \end{bmatrix} \dots\dots\dots(3.13)$$

3.3 STATCOM Model

STATCOM consists of two or multi level voltage source converter (VSC) which employ semiconductor switching devices which can be switched ON and OFF at any time such as IGBT, GTO. The converter is connected to DC side including DC capacitor act as storage device. The STATCOM is connected to AC side through interfacing reactor. The VSC is able of generating or absorbing reactive power which can be used to control the ac voltage of the network at point of common coupling (PCC). The VSC acts as a static reactive power compensator with instantaneous response because the VSC has

no inertia. The STATCOM is used to regulate the reactive power at PCC by injecting quadrature lagging or leading current with system voltage.

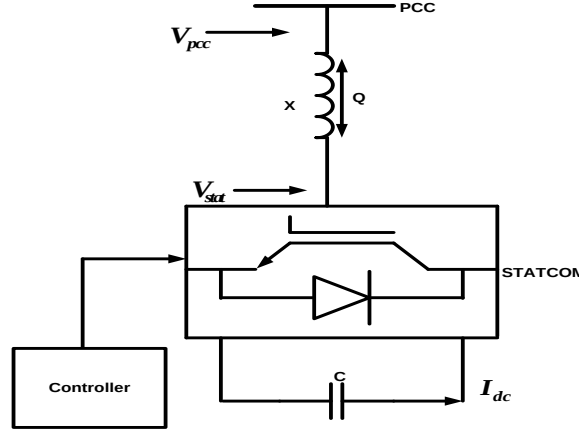


Figure 3.4 STATCOM connection

The reactive power exchange between the STATCOM and PCC is controlled by regulating the STATCOM voltage (V_{stat}) according to the following equation[24], [25]:

$$Q = \frac{3V_{pcc} \cos(\delta)}{X} - \frac{V_{stat}^2}{X} \dots \dots \dots (3.14)$$

Where V_{stat} is STATCOM fundamental output AC phase voltage (rms), V_{pcc} is the fundamental output AC phase voltage (rms) at PCC, X is the leakage reactance of interfacing reactor, and δ is the phase angle between V_{pcc} and V_{stat} . The STATCOM inject capacitive reactive into the system if the magnitude of STATCOM voltage is bigger than the voltage at PCC and absorb inductive reactive power from the system if the magnitude of STATCOM voltage is smaller than the voltage at PCC. The control of STATCOM voltage is achieved using high frequency PWM technique. The STATCOM DC side voltage and STATCOM AC side voltage is given by the following equation :

$$v_{stat} = M \frac{V_{dc}}{2} \sin(\omega t) \dots \dots \dots (3.15)$$

Where M is the modulation index, V_{dc} the dc voltage, ω is the system frequency. The VSC controller system is used to maintain the dc voltage and adjust the variable M to increase or decrease the STATCOM voltage magnitude and hence, control the active and reactive power flows.

The mathematical model of STATCOM in the d-q reference frame is [26]:

$$L \begin{bmatrix} \frac{di_{sd}}{dt} \\ \frac{di_{sq}}{dt} \end{bmatrix} = \begin{bmatrix} V_{dpcc} - V_{dstat} \\ V_{qpcc} - V_{qstat} \end{bmatrix} + \begin{bmatrix} -R & \omega L \\ \omega L & -R \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} \dots\dots\dots (3.16)$$

Where R and L are the parameter of coupling reactor and interfacing transformer

3.3.1 STATCOM Control System

In a converter with sinusoidal PWM the relationship between the modulation index M , DC link voltage, load angle of STATCOM AC voltage and the dq components of the AC voltage are given by [25]:

$$\begin{bmatrix} V_{dstat} \\ V_{qstat} \end{bmatrix} = V_{dc} \frac{M}{2} \begin{bmatrix} \cos \delta \\ \sin \delta \end{bmatrix} \dots\dots\dots (3.17)$$

In order to design an inner current controller the cross coupling in equations (3.16) and (3.17) are decoupled as follow :

$$\begin{bmatrix} v_{dpcc} \\ v_{qpcc} \end{bmatrix} = \begin{bmatrix} u_d \\ u_q \end{bmatrix} + \begin{bmatrix} 0 & -\omega L \\ \omega L & 0 \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} + \begin{bmatrix} v_{dstat} \\ v_{qstat} \end{bmatrix} \dots\dots\dots (3.18)$$

Where the new variable are defined as follow

$$u_d = Ri_{sd} + L \frac{di_{sd}}{dt} = k_{pi}(i_{sd}^* - i_{sd}) + k_{ii} \int (i_{sd}^* - i_{sd}) dt \dots\dots\dots (3.19)$$

$$u_q = Ri_{sq} + L \frac{di_{sq}}{dt} = k_{pi}(i_{sq}^* - i_{sq}) + k_{ii} \int (i_{sq}^* - i_{sq}) dt \dots\dots\dots (3.20)$$

Where k_{pi} and k_{ii} are the propotional and integral gains of the current controller which regulates the current and remains its value during network disturbances to prevent the STATCOM components from experiencing high current stresses that may lead to their destruction. The references values (i_{sd}^* & i_{sq}^*) are obtained using outer loops controller.

The reference currents for the inner controller as follows:

$$i_{sd}^* = k_{pdc}(V_{dc}^* - V_{dc}) + k_{idc} \int (V_{dc}^* - V_{dc}) dt \dots\dots\dots (3.21)$$

$$i_{sq}^* = k_{pac}(V_{pcc}^* - V_{pcc}) + k_{iac} \int (V_{pcc}^* - V_{pcc}) dt \dots\dots\dots (3.22)$$

Where k_{pdc} and k_{idc} are the propotional and integral gains of the DC voltage controller and k_{pac} and k_{iac} are the propotional and integral gains of the AC voltage controller.

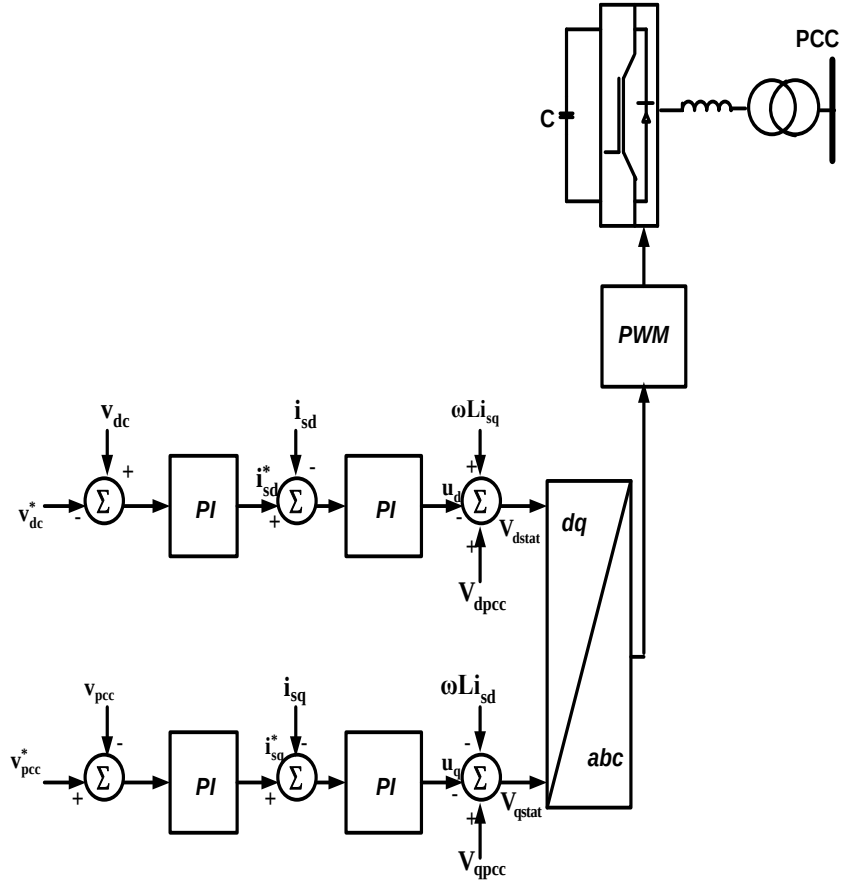


Figure 3.5 STATCOM control system block diagram.

3.3.2 Modeling of Space Vector PWM

The power electronic converter can operate only eight distinct topologies. Six out of these eight topologies produce a nonzero output voltage and are known as active vectors ($V_1 - V_6$) and the remaining two topologies produce a zero output voltage and are known as zero vectors (V_0, V_7). The six active vectors are forming a regular hexagon and six sectors numbered S-I to S-VI in a stationary reference frame as shown in Figure 3.6. Since the zero vectors have a zero magnitude and phase angle, the positions of these vectors are at the origin as shown in Figure 3.6. The active vectors $V_1 - V_6$ are obtained as follows :

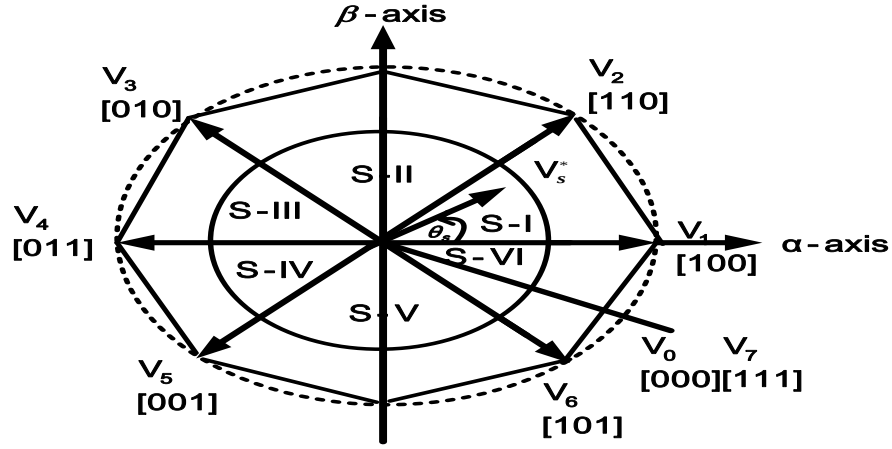


Figure 3.6 Representation of the inverter states in the stationary reference frame.

$$V_k = \sqrt{(2/3)}V_{dc}e^{j(k-1)(\pi/3)} \dots\dots\dots(3.23)$$

Here, $k=1,2,\dots,6$.

It is seen from Eq(3.23) that the magnitudes of all active vectors are the same and the angle between any adjacent two active vectors is 60 deg. Let the desired voltage in a stationary ($\alpha - \beta$ axis) reference frame is V_s^* . Then, the vector, magnitude, and angle of the desired voltage can be given as follows:

$$V_s^* = |V_s^*|e^{j\theta_s^*} \dots\dots\dots(3.24)$$

$$V_s^* = |V_s^*|e^{j\theta_s^*} \dots\dots\dots(3.25)$$

$$\theta_s^* = \tan^{-1}[V_{s\beta}^* / V_{s\alpha}^*] \dots\dots\dots(3.26)$$

$$|V_s^*| = \sqrt{V_{s\alpha}^{*2} + V_{s\beta}^{*2}} \dots\dots\dots(3.27)$$

Looking at Figure 3.6 one finds that, assuming V_s^* to be lying in sector k , the adjacent active vectors are V_k and V_{k+1} . To achieve the desired stator voltage V_s^* within the sampling time T_s , the active voltage vectors V_k and V_{k+1} should be activated during the time T_k and T_{k+1} , respectively. Hence, the on-time T_k and T_{k+1} are evaluated by the following equations:

$$V_s^*T_s = V_kT_k + V_{k+1}T_{k+1} \dots\dots\dots(3.28)$$

Splitting this vectorial equation into real and imaginary components, from Eqs. (3.23)–(3.27) follows that:

$$\begin{bmatrix} T_k \\ T_{k-1} \end{bmatrix} = \frac{2T_s|V_s^*|}{\sqrt{3}k_T V_{dc}} \begin{bmatrix} \sin[\frac{k\pi}{3} - \Theta_s^*] \\ \sin[\Theta_s^* - \frac{(k-1)\pi}{3}] \end{bmatrix} \dots\dots\dots(3.29)$$

where the constant k_T is arbitrary and the value may be chosen equal to $2/3$ or $\sqrt{2/3}$ The on-time for the zero state vectors is obtained by the following equation:

$$T_0 = T_s - (T_k + T_{k+1}) \dots\dots\dots(3.30)$$

Table 3.1 Sequence of selected vectors with respect to time.

Sector/time	$T_0/4$	$T_k/2$	$T_{k+1}/2$	$T_0/2$	$T_{k+1}/2$	$T_k/2$	$T_0/4$
S-I	V_0	V_1	V_2	V_7	V_2	V_1	V_0
S-II		V_3	V_2		V_2	V_3	
S-III		V_3	V_4		V_4	V_3	
S-IV		V_5	V_4		V_4	V_5	
S-V		V_5	V_6		V_6	V_5	
S-VI		V_1	V_6		V_6	V_1	

In order to obtain optimal harmonic performance and the minimum switching frequency for each of the power devices, the vector sequences are arranged such that the transition from one vector to the next is performed by switching only one converter leg. Therefore, the request minimum number of commutations per cycle is met if the active vectors are selected as Table 3.1. When $T_k + T_{k+1} > T_s$ the time T_k and T_{k+1} are simply rescaling as follows:

$$\begin{bmatrix} T'_k \\ T'_{k+1} \end{bmatrix} = \frac{T_s}{T_k + T_{k+1}} \begin{bmatrix} T_k \\ T_{k+1} \end{bmatrix} \dots\dots\dots(3.31)$$

so that $T'_k + T'_{k+1} = T_s$ and $T_0 = 0$. According to this rescaling process, the converter can operate up to the modulation index 0.952. Applying the special switching in the SVM process of a PWM inverter the inverter can be operated up to the modulation index 1.155 [27]

3.4 STATCOM Transient Stability Model

The STATCOM generates a balanced 3-phase voltage whose magnitude and phase can be adjusted rapidly by using semiconductor switches. The STATCOM is composed of a voltage source inverter with a dc capacitor, coupling transformer, and signal generation and control circuit the inverter output voltage magnitude is controlled by modulation index ($0 \leq m \leq 1$)

$$P = VV_{statcom} \sin(\delta - \alpha)/X \dots\dots\dots (3.32)$$

For decreasing of output voltage harmonics of STATCOM we are using the SPWM technique

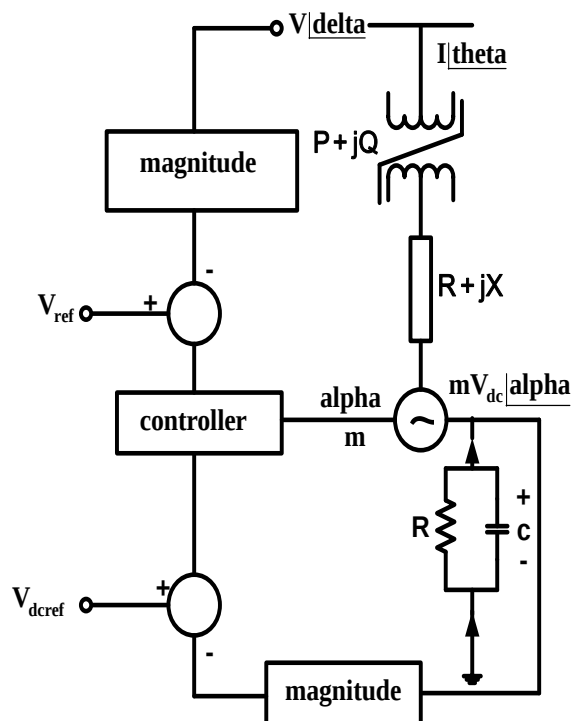


Figure 3.7 Transient stability model of a STATCOM with SPWM voltage control.

Assuming balanced, fundamental frequency voltages, the controller can be accurately represented in transient stability studies using the basic model shown in Figure 3.7.

The differential algebraic equations corresponding to this model are:

$$\begin{bmatrix} \dot{x}_c \\ \dot{\alpha} \\ \dot{m} \end{bmatrix} = f(x_c, \alpha, m, V, V_{dc}, V_{ref}, V_{dcref}) \dots \dots \dots (3.33)$$

$$\dot{V}_{dc} = \left(\frac{VI}{CV_{dc}} \right) \cos(\delta - \Theta) - G_c V_{dc}/C - RI^2/CV_{dc} \dots \dots \dots (3.34)$$

$$0 = \begin{bmatrix} P - VI \cos(\delta - \Theta) \\ Q - VI \sin(\delta - \Theta) \\ P - V^2 G + KV_{dc}VG \cos(\delta - \alpha) + KV_{dc}VB \sin(\delta - \alpha) \\ Q + V^2 B - KV_{dc}VB \cos(\delta - \alpha) + KV_{dc}VG \sin(\delta - \alpha) \end{bmatrix} \dots \dots \dots (3.35)$$

Where most of the variables are explained on Figure(3.7); $G_c = I/R_c$; $G + jB = 1/(R + jX)$, which is used to represent the transformer impedance, $K = (\sqrt{3}/8)m$, and hence is directly proportional to the modulation index m ; and X_c and $f(\cdot)$ stand for the internal control system variables and equations, respectively [28].

3.5 Summary

In this chapter different components of power system has been modeled such as synchronous machine flux model and current model, excitation system, Hydro Turbine-Governor system, space vector PWM and STATCOM with its control system, also STATCOM transient stability model has been discussed.

Chapter Four

Results and Discussion

4.1 Introduction

Today transmission and distribution network of power systems are very stressed due to growing demand of better quality of power at lower cost. As a result transmission networks are operating on high transmission levels. Transient stability and damping oscillations are the major operating problems that power engineers are confronting during transmitting power at high levels. Transient stability indicates the capability of the power system to maintain synchronism when subjected to a severe transient disturbances such as fault on heavily loaded lines, loss of large load. Generator excitation controller with only excitation control can improve transient stability for minor faults but it is not sufficient to maintain stability of system for large faults occur near to generator terminals. Researchers worked on other solution and found that flexible ac transmission systems (FACTS) is one of the most prominent solution that can improve stability by changing electrical characteristics of power system. A static synchronous compensator is one of the FACTS device operated on principle of reactive power compensation can use to improve the transient stability of the system by increasing (decreasing) the power transfer capability when the machine angle increases (decreases) [29]

In this chapter the ability of STATCOM to maintain the transient stability will be investigated by studying two machine system model when a fault occur on the system and the system installed without STATCOM. After that the effect of STATCOM in improvement of the transient stability will be studied by connecting STATCOM of 200 MVA at midpoint of transmission line of the two machine system. Then the study will be extended to a multi machine system, the model will be used IEEE 3-machine 9-bus system, firstly the system will be studied when the fault occur in the system and without presence of STATCOM, secondly the same system will be investigated but with installation of STATCOM.

4.2 Simulation Model of Two Machine System

Simulink Model of two machines (M1 and M2) system are shown in Figure 4.1 to Figure 4.4. Machine M1 represent 1000 MW hydraulic generation plant while Machine M2 represents 5000 MW generating plant. Each machine supplied with a Governor, Excitation system and power system stabilizer. The two machines are connected through a 500kV, 700km transmission line. Resistive load of 5000 MW connected on Machine M2 side. GTO based STATCOM having rating of 200 MVA connected at midpoint of transmission line.

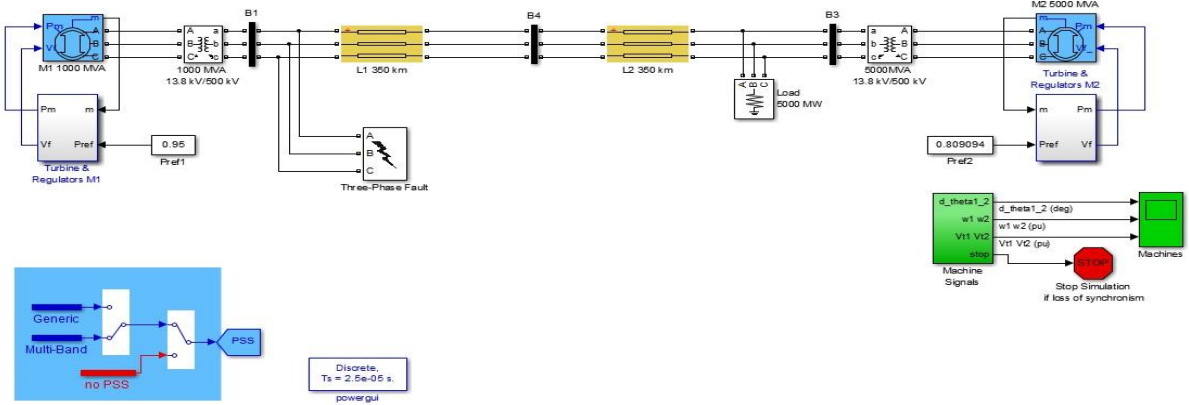


Figure 4.1 Two machine system installed without STATCOM

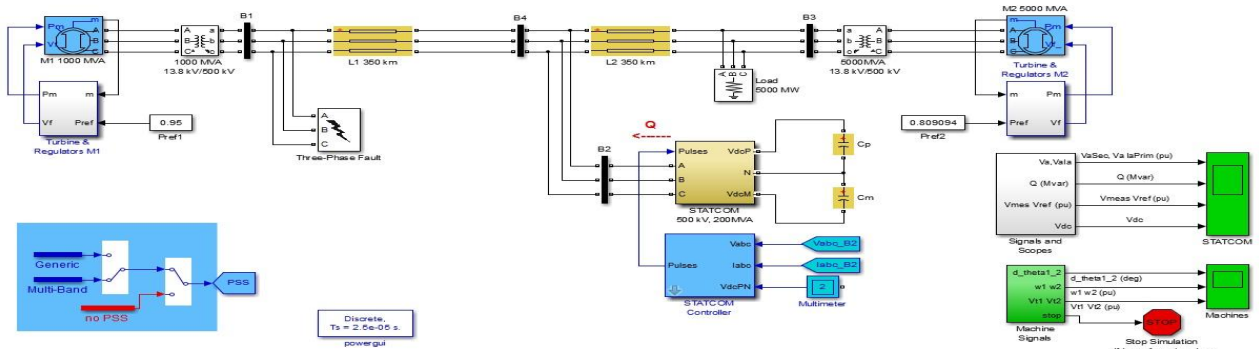


Figure 4.2 Two machine system installed with STATCOM

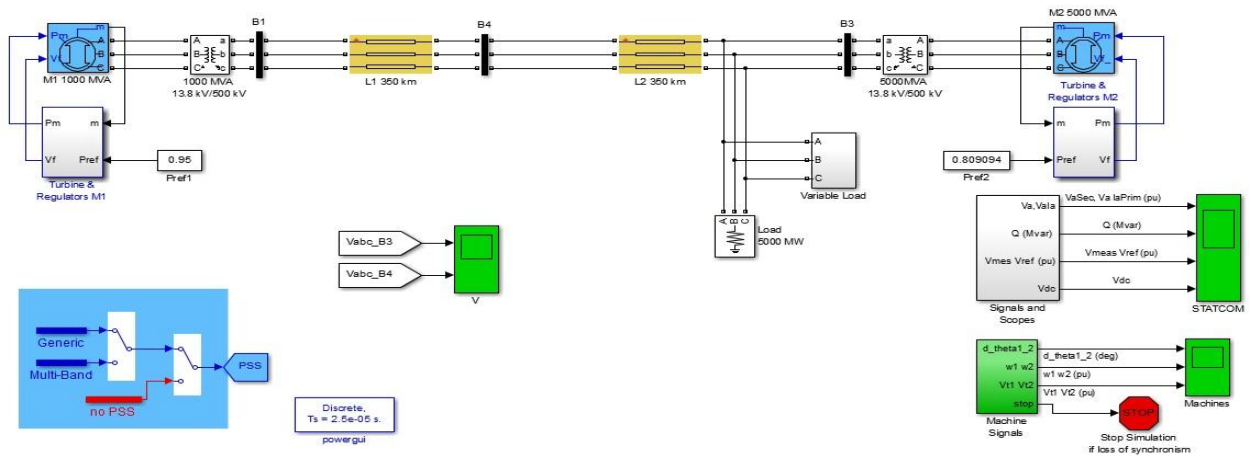


Figure 4.3 Two machine system installed with step changing load without STATCOM

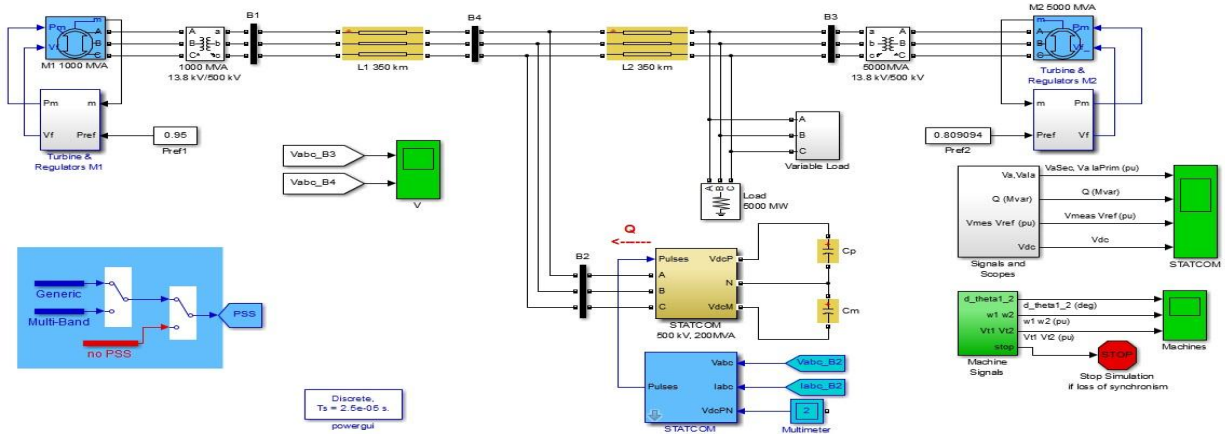


Figure 4.4 Two machine system installed with step changing load and STATCOM

4.3 Simulation Results of Two Machines System

Simulation results are obtained using MATLAB/SIMULINK for two machine system as Figure 4.1 to Figure 4.4 illustrate. Firstly the system has been analysed without implementation of a STATCOM and the results of a three phase fault at bus 1 has been studied. Thereafter the system has been analysed with a STATCOM and the improvement in the transient stability has been investigated. Secondly the system has been analysed without implementation of a STATCOM and the results when a step changing load is connected near bus 3 have been obtained. Then the system has been

analysed with a STATCOM , the improvement in the transient stability also has been investigated.

4.3.1 Two Machine System Installed without STATCOM

A three phase fault with clearing time of 0.1 sec occurred at 1 sec. It is noted that the rotor angle deviation increased indefinitely when the fault is cleared at 0.1 sec, so the system became unstable as illustrated in Figure 4.5

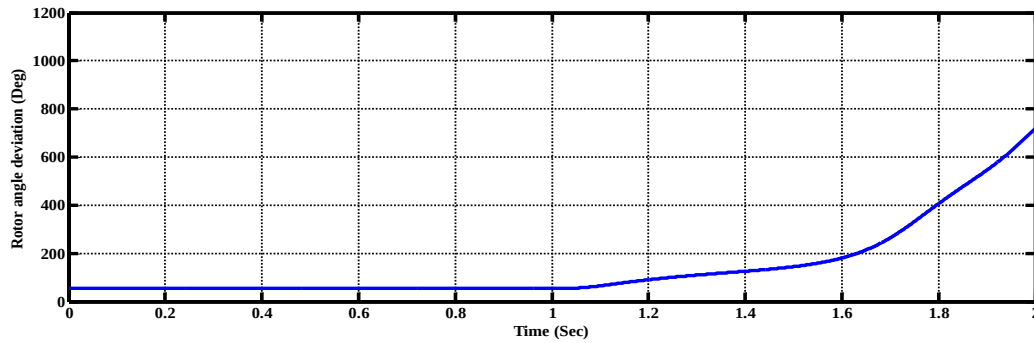


Figure 4.5 Rotor angle deviation with time

It can be seen from Figure 4.6, for FCT=0.1 sec and without STATCOM controller implemented in the system, the speed of the first machine W1 increase indefinitely and the speed of the second machine W2 decrease indefinitely, so at this critical situation the system loss stability

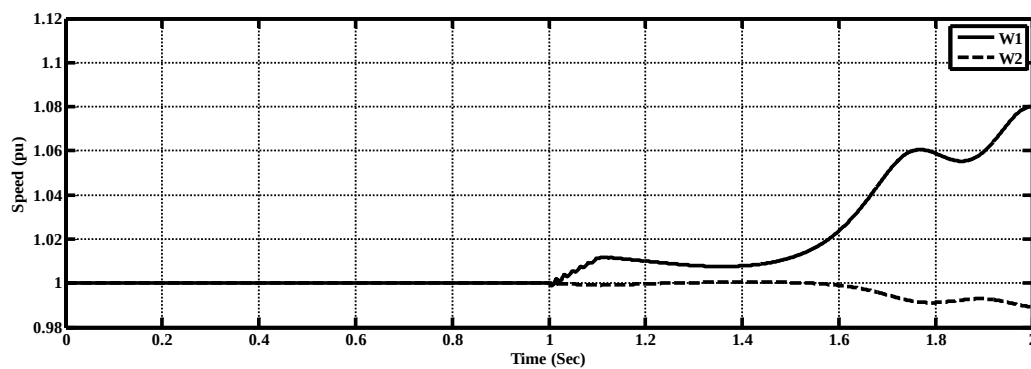


Figure 4.6 Speed with time

At 1 sec the terminal voltage of the first machine decreased to 0.3233 pu , after the fault cleared at 0.1 sec it increased indefinitely while the the terminal voltage of the second

machine decreased to 0.956 pu during the fault and after the critical clearing time it became unstable as Figure 4.7 illustrate.

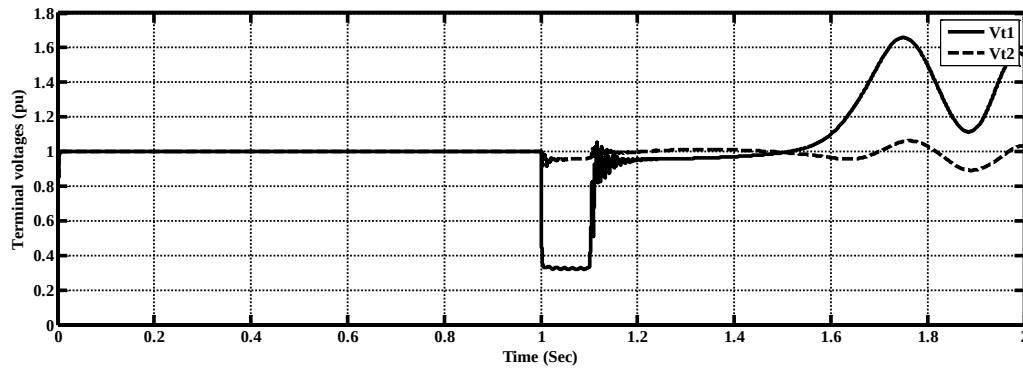


Figure 4.7 Terminal voltages with time

4.3.2 Two Machine System Installed with STATCOM

It is clear from Figure 4.8 that when a three phase fault with clearing time of 0.1 sec occurred at 1 sec the rotor angle deviation began to oscillate but quickly after the fault has been cleared the oscillation damped out and the system became stable due to presence of STATCOM.

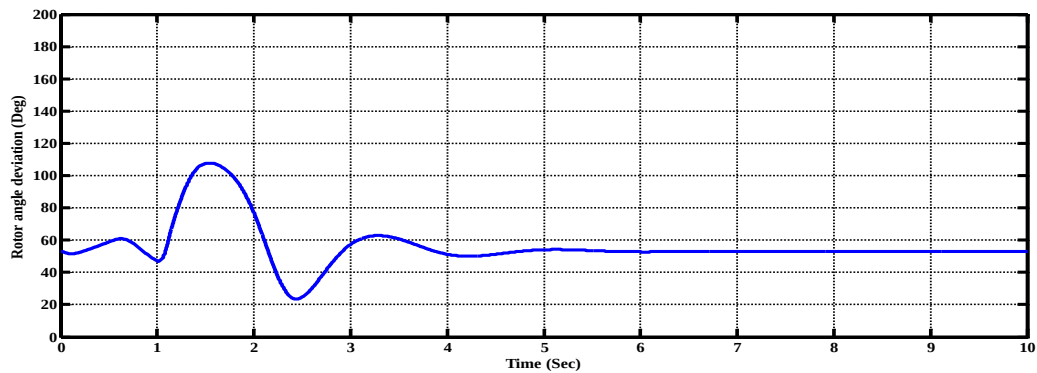


Figure 4.8 Rotor angle deviation considering STATCOM

Figure 4.9 shows the angular speed for fault cleared at 0.1 sec, the speeds of two machines are damped and consequently the system is stable.

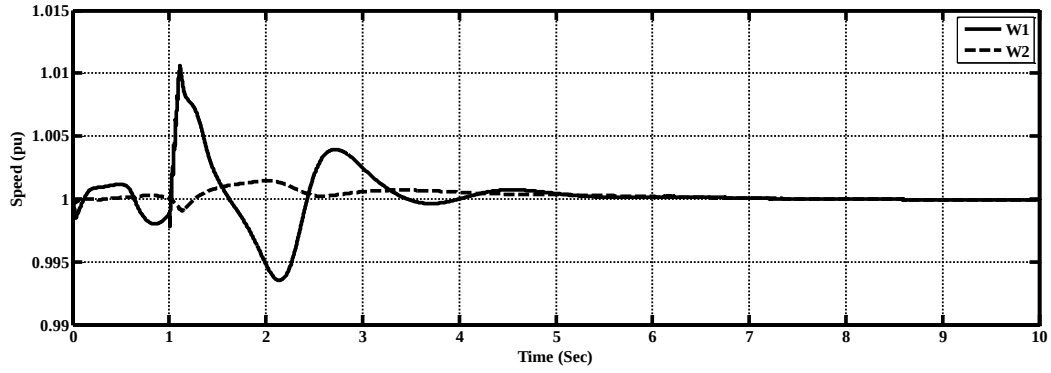


Figure 4.9 Speed variation with time considering STATCOM

Observation from Figure 4.10 shows that during the disturbance V_{t1} decreased to 0.3145 pu and V_{t2} decreased to 0.9442 pu, after the disturbance those voltages are less oscillated and stabilized faster.

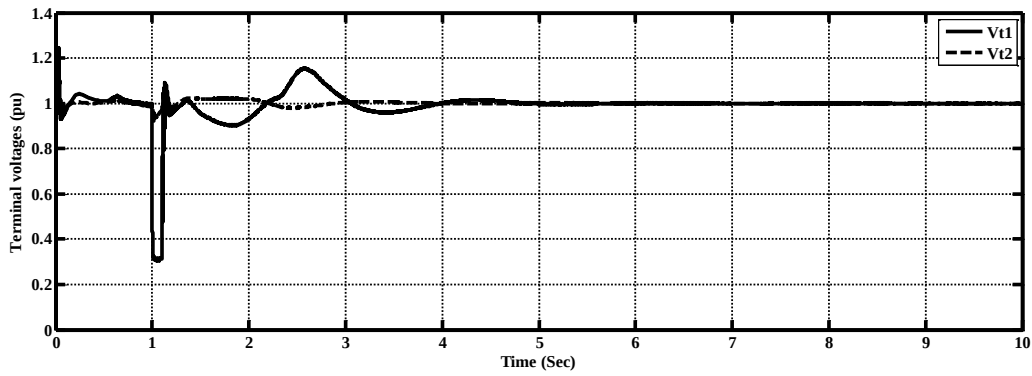


Figure 4.10 Variation of terminal voltages considering STATCOM

From Figure 4.11 it is clear that STATCOM is able to inject significant reactive power into the system to maintain the transient stability, when a three phase fault occurred at 1 sec STATCOM injected 349.4 Mvar to the system during this severe disturbance.

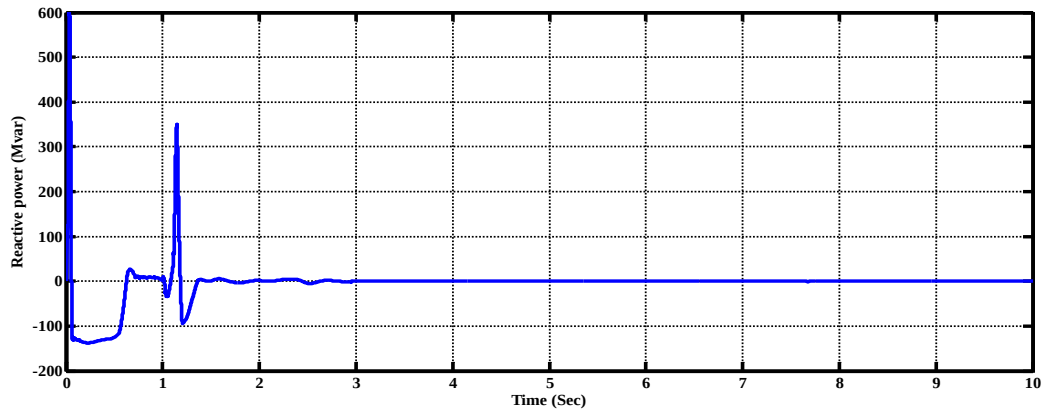


Figure 4.11 STATCOM Reactive Power with time

Figure 4.12 shows V_{meas} and V_{ref} , when a severe disturbance occurred at 1 sec V_{meas} is decreased to 0.4655 pu, after the fault is cleared at 0.1 sec V_{meas} is oscillated around 1.0 pu then the oscillations died out to settle at 1.0 pu.

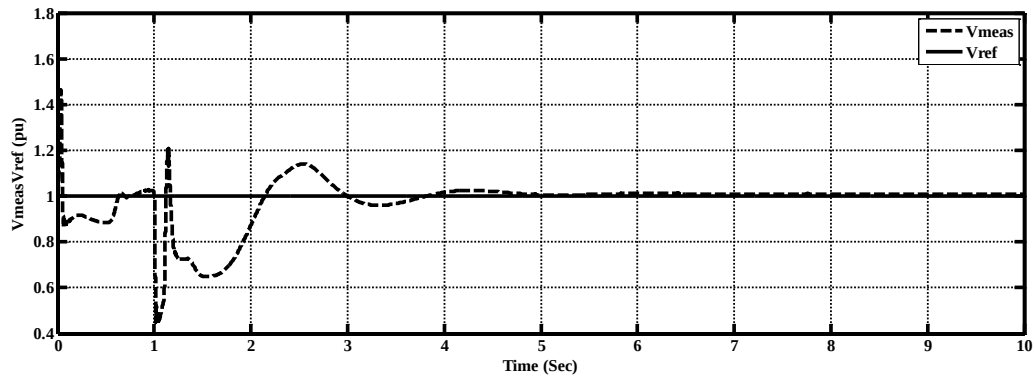


Figure 4.12 Variation of V_{meas} V_{ref} with time

Before the disturbance the voltage across the capacitor is 20 kV, during the disturbance the capacitor charges further and V_{dc} reaches to 67.11 kV, after the disturbance V_{dc} returned back to 20 kV as Figure 4.13 illustrate.

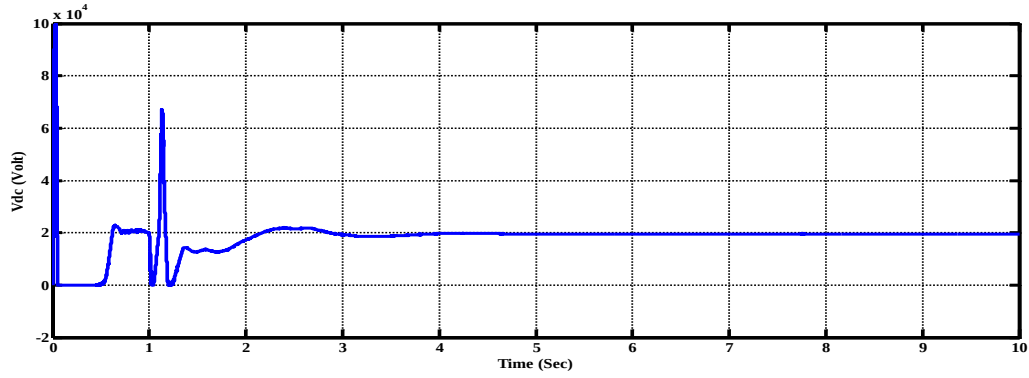


Figure 4.13 Variation of Vdc with respect to time

4.3.3 Two Machine System Installed with Step Changing Load without STATCOM

Figure 4.14 shows rotor angle deviation for the system installed with step changing load and without STATCOM, when a load is increased by 1000 MW from 4 sec to 6 sec ,the first swing of the rotor angle deviation reached to 85.76° , then settled to its steady state value. From 14 sec to 16 sec the load is decreased by 1000 MW, the first swing of the rotor angle deviation decrease to 35.49° then the oscillations died out.

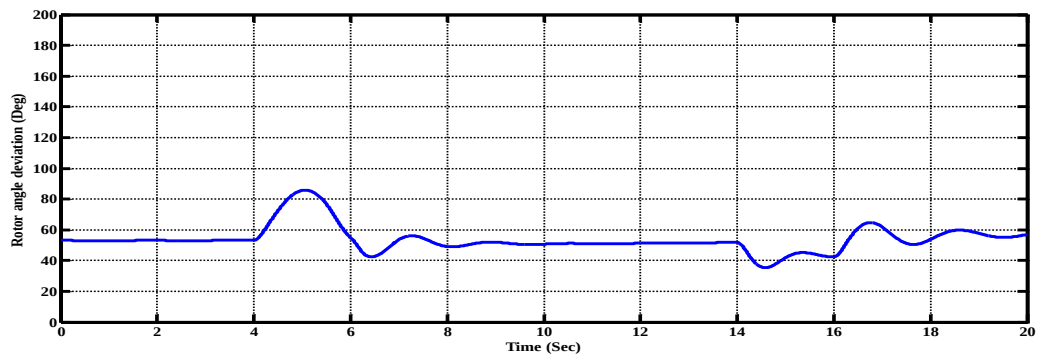


Figure 4.14 Rotor angle deviation without considering STATCOM

Figure 4.15 shows the terminal voltages of the two machines, when the load is increased by 1000 MW from 4 sec to 6sec, the terminal voltage of machine 1 decreased to 0.9263 pu and the terminal voltage of machine 2 decreased to 0.9598 pu, after this disturbance both machines terminal voltages returned to 1 pu. From 14 sec to 16 sec the load is decreased by 1000 MW, the terminal voltage of machine 1 is increased to 1.108 pu and the terminal voltage of machine 2 is increased to 1.067 pu.

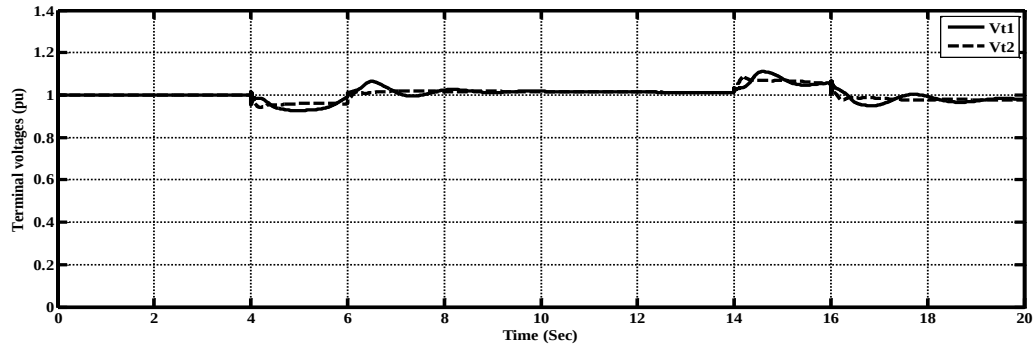


Figure 4.15 Variation of terminal voltages with time without considering STATCOM

During the load increase from 4 sec to 6 sec it is observed that three phase voltage of bus 3 is decreased to 0.9339 pu, after the load increase duration it returned back to 1.0 pu. When the load decrease in the interval from 14 sec to 16 sec the voltage is increased to 1.066 pu, after this disturbance it returned back to 1.0 pu as Figure 4.16 illustrate.

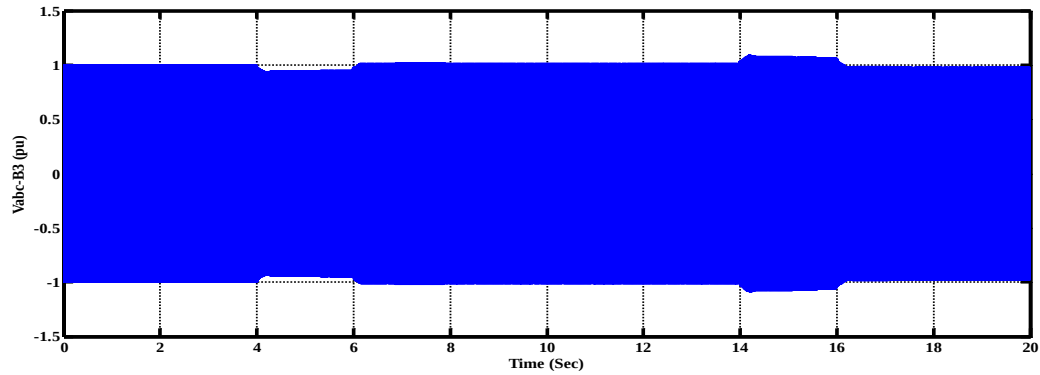


Figure 4.16 Variation of V-Bus 3 with respect to time without considering STATCOM

When the load increase in the interval from 4 sec to 6 sec the three phase voltage of bus 4 is decreased to 0.7509 pu, and during the load decrease from 14 sec to 16 sec the voltage is increased to 1.172 pu as Figure 4.17 illustrate.

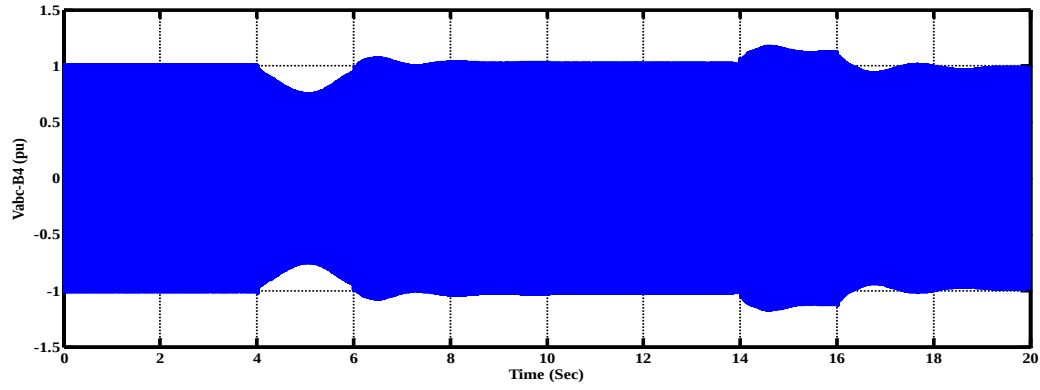


Figure 4.17 Variation of V-Bus 4 with respect to time without considering STATCOM

4.3.4 Two Machine System Installed with Step Changing Load and STATCOM

Figure 4.18 shows rotor angle deviation for the system installed with step changing load and STATCOM, when the load is increased by 1000 MW from 4 sec to 6 sec, the first swing of the rotor angle deviation reached to 70.25° which indicates improvement in the transient stability from the case when the system installed without STATCOM, after this disturbance the rotor angle deviation settled to its steady state value. From 14 sec to 16 sec the load is decreased by 1000 MW, the rotor angle deviation also swings and the first swing decrease to 37.18°

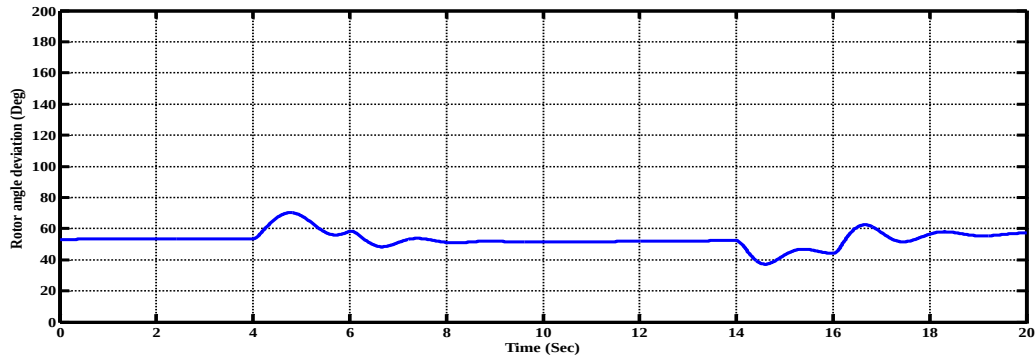


Figure 4.18 Rotor angle deviation considering STATCOM

From Figure 4.19, it is observed that the terminal voltage of machine 1 is decreased to 0.9324 pu and machine 2 to 0.9553 pu from 4 sec to 6 sec when the load increased by 1000 MW, during the the load decrease by 1000 MW from 14 sec to 16 sec the terminal voltage of machine 1 is increased to 1.099 pu and machine 2 to 1.07 , it is clear that the

terminal voltage stability of machine 1 is improved when the system installed with STATCOM.

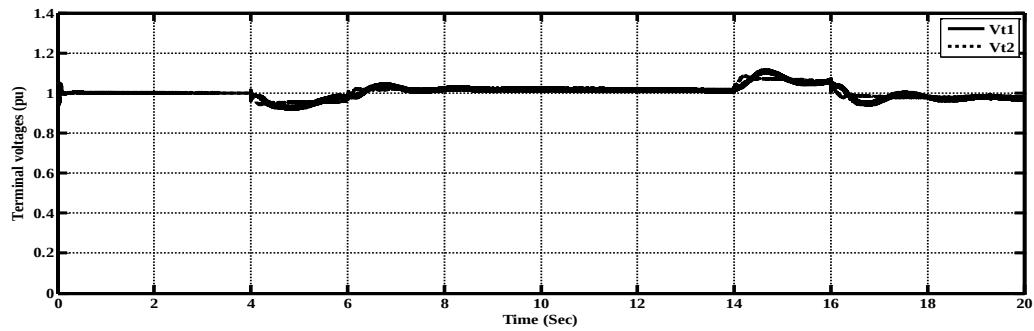


Figure 4.19 Terminal voltages with time considering STATCOM

It can be noticed from Figure 4.20 that the STATCOM has manipulated its reactive power exchange with the system to maintain the transient stability of the system. It can be seen that when the load increased from 4 sec to 6 sec the STATCOM injected 79.55 Mvar to the system, during the load decrease interval from 14 sec to 16 sec it absorbed 86.47 Mvar reactive power from the system.

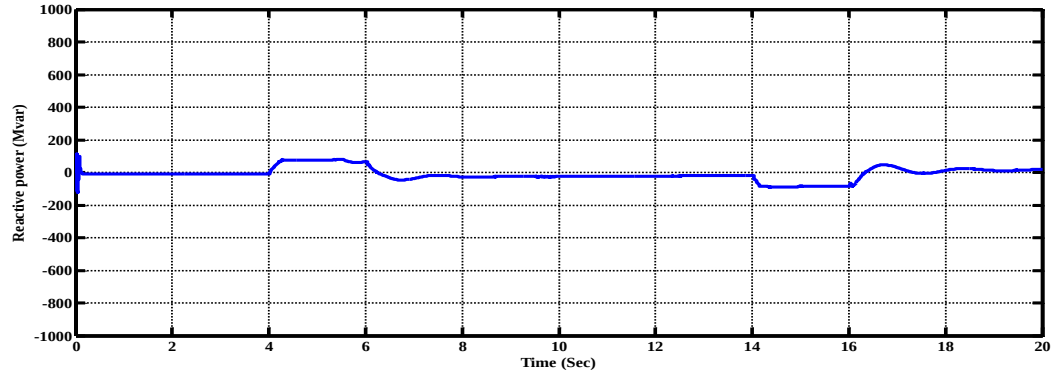


Figure 4.20 Reactive power

It can be seen from Figure 4.21 when the load increased from 4 sec to 6 sec the measured voltage V_{meas} decreased to 0.9122 pu and during the load increase interval from 14 sec to 16 sec it increased to 1.108 pu.

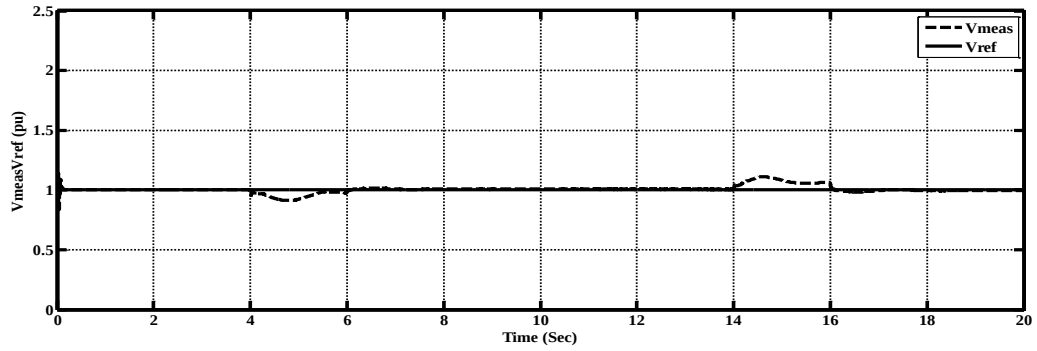


Figure 4.21 Vmeas Vref with time

From Figure 4.22 it is observed that during the load increase from 4 sec to 6 sec the capacitor charges and Vdc reaches to 23 kV, when the load decreased from 14 sec to 16 sec the capacitor discharges and Vdc falls to 16.21 kV.

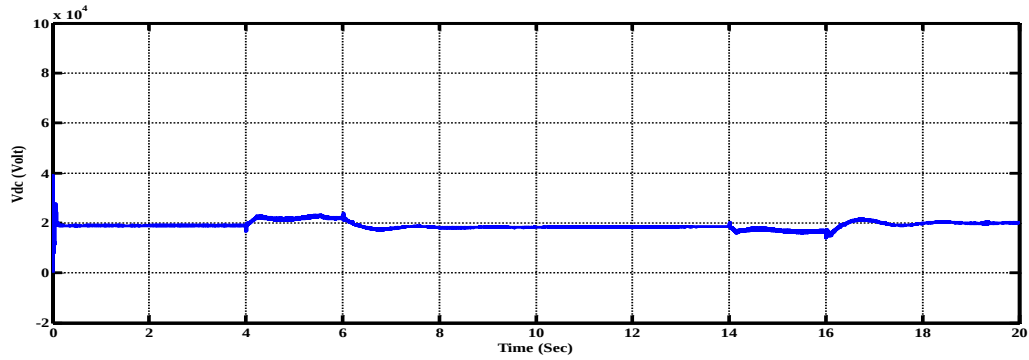


Figure 4.22 Vdc with respect to time

From Figure 4.23 it can be seen that during the load increase from 4 sec to 6 sec it is noted that the voltage of bus 3 decreased to 0.940 pu, after the load increase duration it returned back to 1.0 pu. When the load decreased in the interval from 14 sec to 16 sec the voltage is increased to 1.063 pu. This result indicates the ability of STATCOM to enhance the voltage stability.

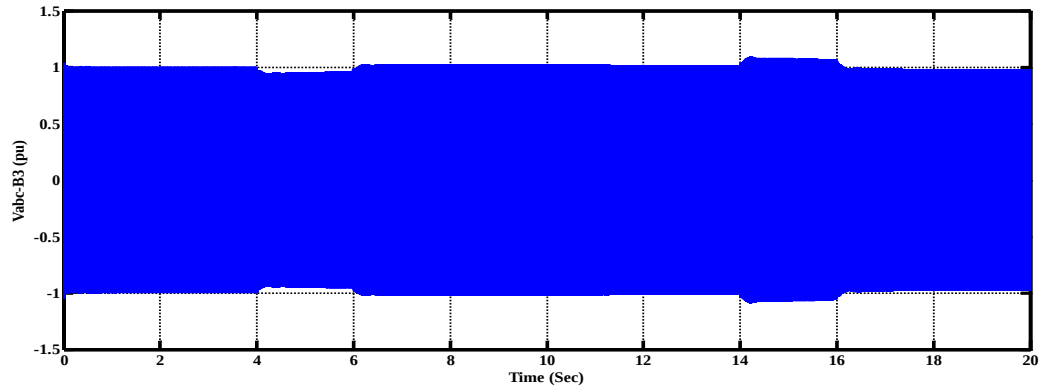


Figure 4.23 V-Bus 3 with time considering STATCOM

Figure 4.24 shows the voltage of bus 4 waveform which illustrating the STATCOM capability to provide voltage support. It can be observed that when the load increased from 4 sec to 6 sec the voltage at B4 is decreased to 0.9229 pu but it recovered quickly to 1.0 pu. When the load decreased from 14 sec to 16 sec the voltage increased to 1.118 pu then returned to 1.0 pu

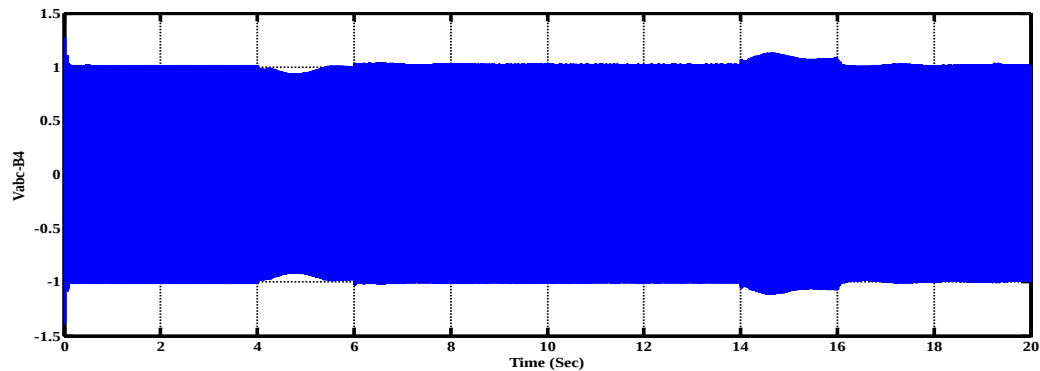


Figure 4.24 V-Bus 4 with time considering STATCOM

4.4 Simulation Model of Multi-Machine System

For Multi-machine system, it is considered the popular IEEE 3-Machine 9-Bus system as shown in Figure 4.25. The base MVA is 100, and system frequency is 60 Hz. The system data are given in Appendix B. The system has been simulated with a classical model for the generators. The disturbance initiating the transient is a three-phase fault occurred at bus 7. To enhance the transient stability STATCOM is connected at bus 8 as shown in Figure 4.26

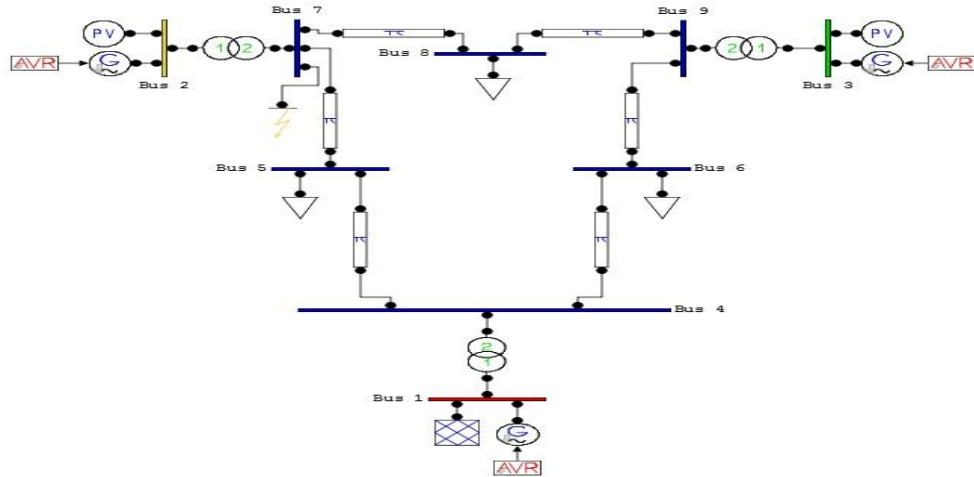


Figure 4.25 IEEE 3-machines 9-bus system installed without STATCOM

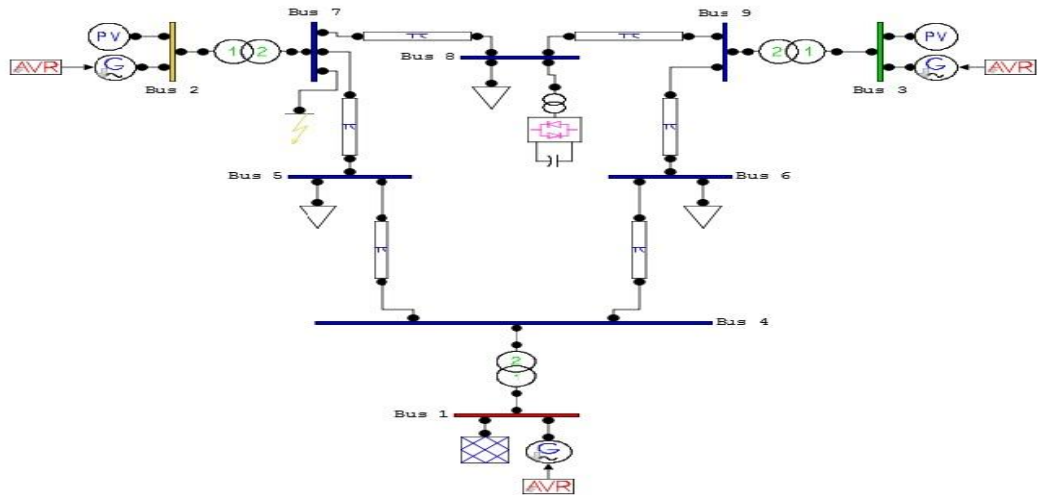


Figure 4.26 IEEE 3-machine 9-bus system installed with STATCOM

4.5 Simulation Results of Multi-Machine System

Simulation results are obtained using PSAT for multi-machine system as Figure 4.25 and Figure 4.26 illustrate. Firstly the system has been analyzed without STATCOM and the results of a three phase fault at bus 7 has been studied. Then the system has been analyzed with a STATCOM and the improvement in the transient stability has been investigated.

4.5.1 Multi-Machine System without STATCOM

The fault is set to occur at 1 sec. It can be seen that when the fault is cleared at 0.2 sec the relative angles (δ_{12} , δ_{13}) increased indefinitely, so at this critical situation the system loss stability as well illustrated in Figure 4.27 and Figure 4.28

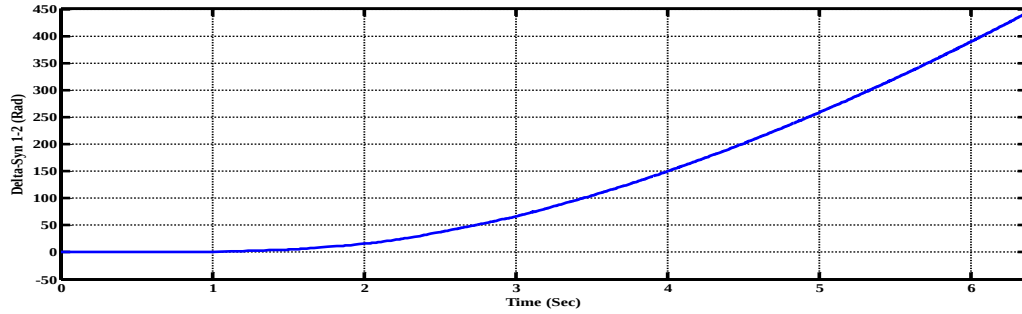


Figure 4.27 Relative angle Delta-Syn 1-2 with time

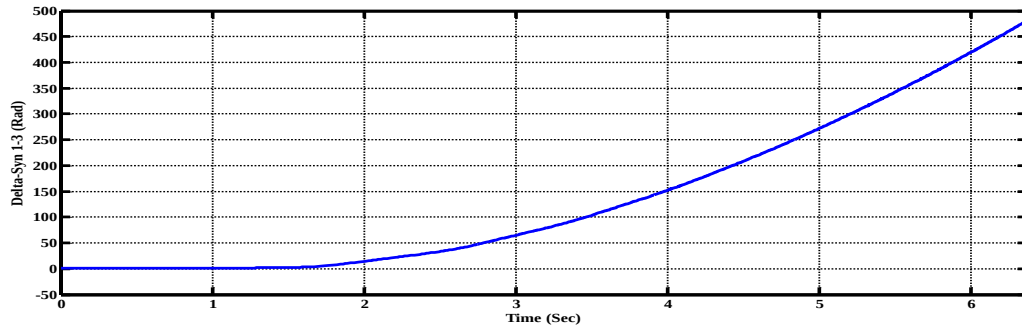


Figure 4.28 Relative angle Delta-Syn 1-3 with time

Figure 4.29, Figure 4.30 and Figure 4.31 show the speed of the three generators for fault cleared at 0.2 sec. It can be observed that the speed of the second and third generator (ω_2 and ω_3) are dramatically increased and the speed of first generator ω_1 decreased indefinitely which indicate that the system became unstable.

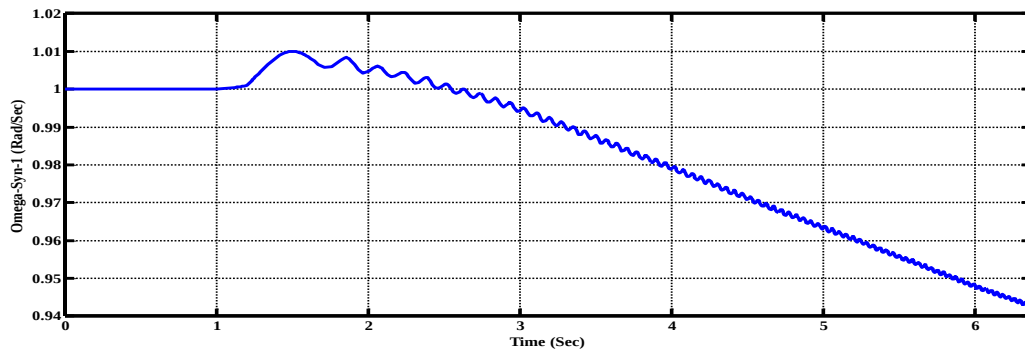


Figure 4.29 Speed variation of generator-1 with time

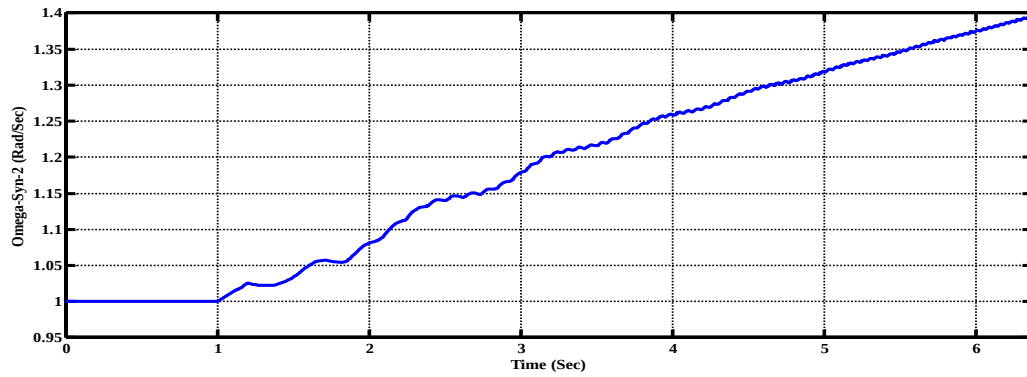


Figure 4.30 Speed variation of generator-2 with time

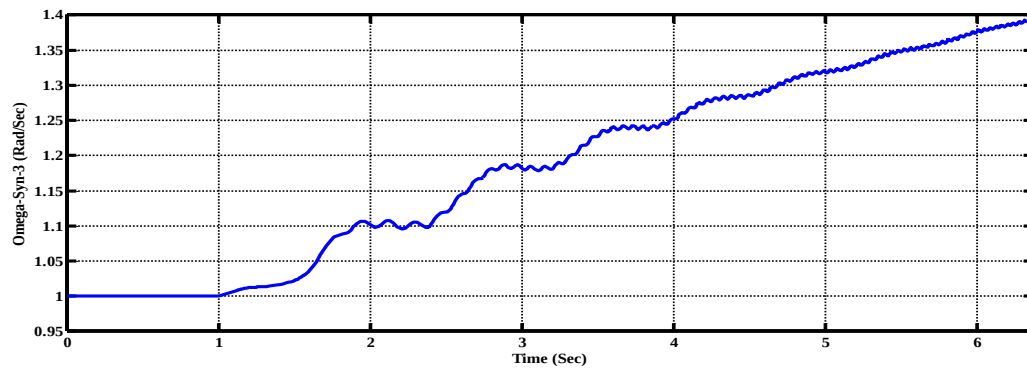


Figure 4.31 Speed variation of generator-3 with time

From Figure 4.32, Figure 4.33 and Figure 4.34 it can be observed that when the fault occurred at 1 sec. the voltage V-Bus 1, V-Bus 7 and V-Bus 8 decreased to 0.8503 pu, 0.009819 pu and 0.2026 pu respectively after the fault is cleared the system became unstable because the oscillations never damped out.

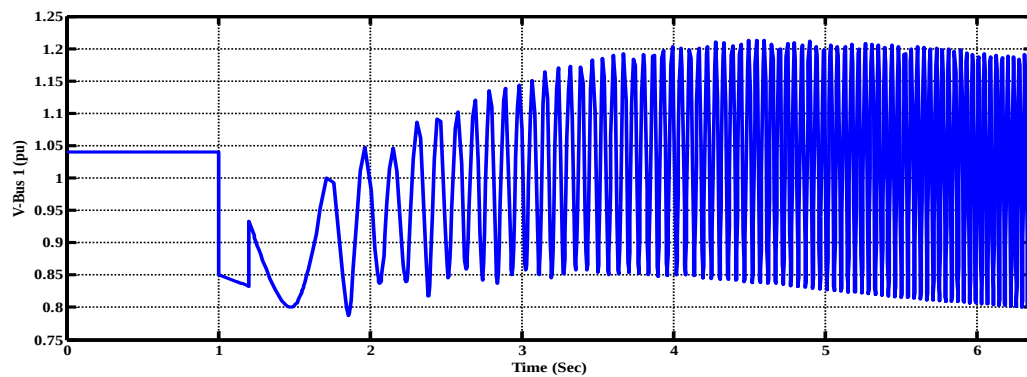


Figure 4.32 Voltage of Bus 1 with time

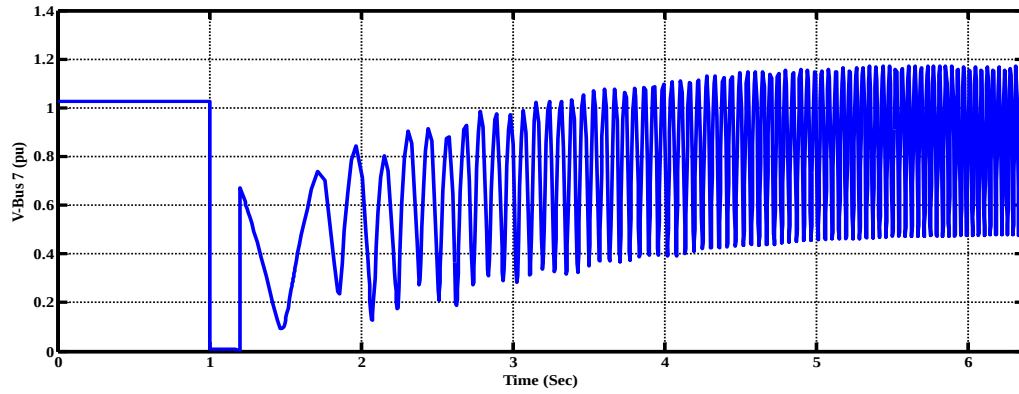


Figure 4.33 Voltage of Bus 7 with time

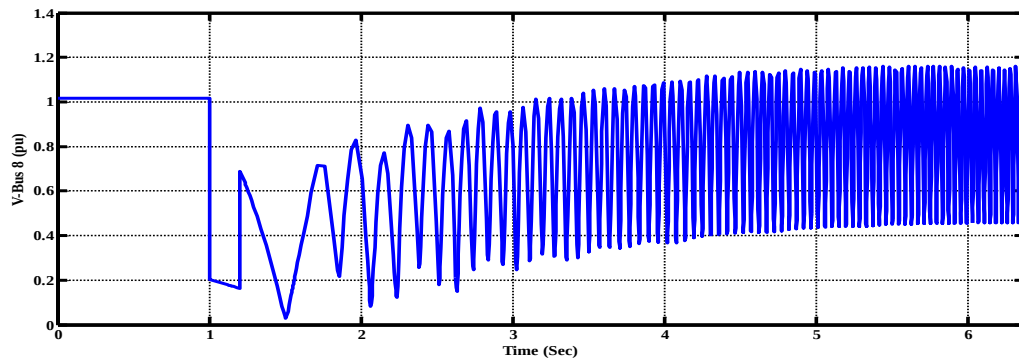


Figure 4.34 Voltage of Bus 8 with time

Figure 4.35, Figure 4.36 and Figure 4.37 show the individual generator electrical and mechanical power for the system with FCT=0.2 sec. The results show that after the fault is cleared the oscillations are not damped out which indicate that the system became unstable.

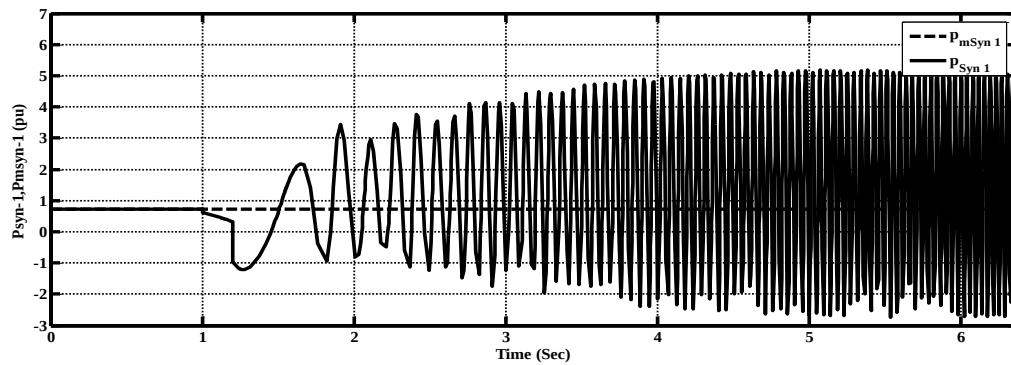


Figure 4.35 Electrical power and mechanical power of generator-1

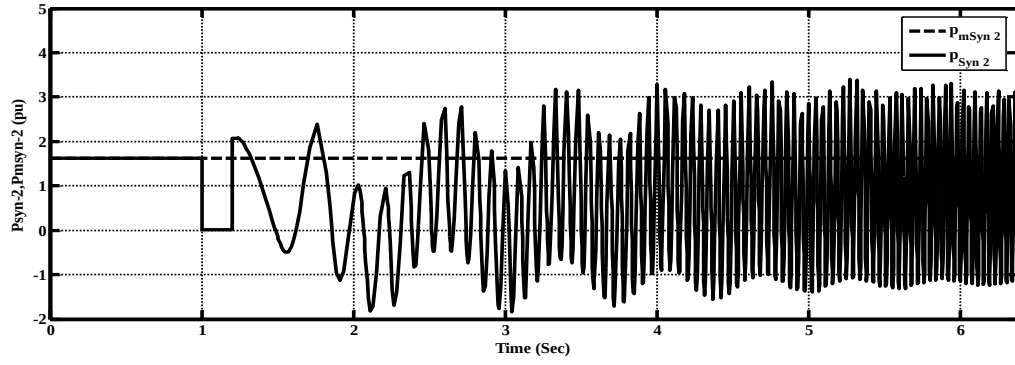


Figure 4.36 Electrical and mechanical power of generator-2

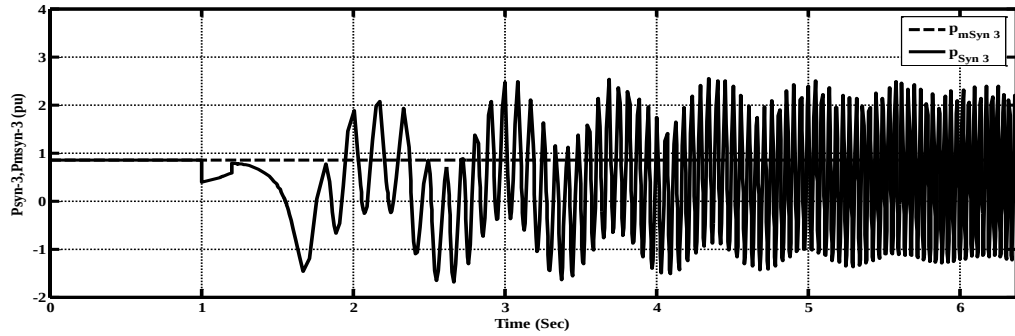


Figure 4.37 Electrical and mechanical power of generator-3

4.5.2 Multi-Machine System with STATCOM

Time domain simulation performed at the cleared time 0.2 sec, it can be seen from Figure 4.38 and Figure 4.39 the maximum relative rotor angles are ($\delta_{12}=2.938$ rad, $\delta_{13}=1.759$ rad), the relative rotor angles are damped and therefore the system oscillations are going to die out compared to the first case (undamped oscillations).

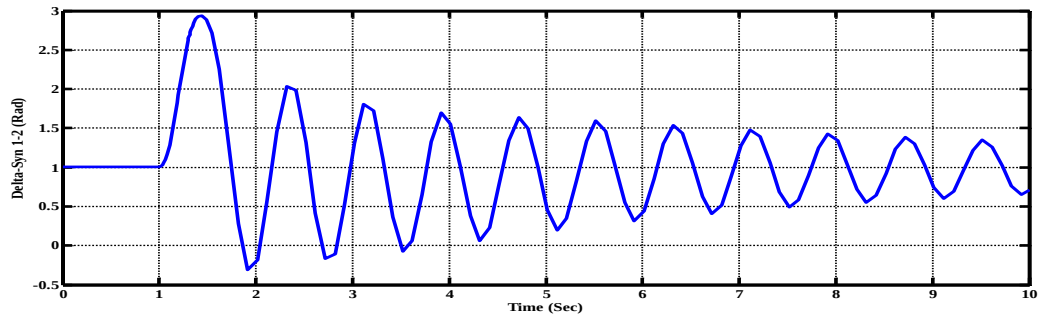


Figure 4.38 Relative rotor angle Delta-Syn 1-2 with time considering STATCOM

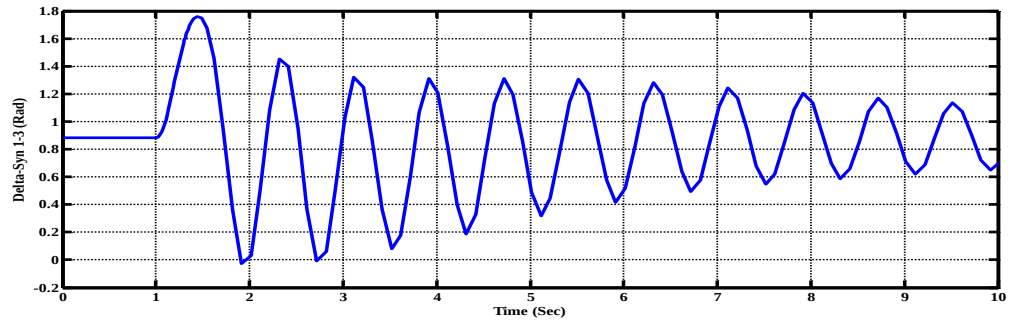


Figure 4.39 Relative rotor angle Delta-Syn 1-3 with time considering STATCOM

Figure 4.40, Figure 4.41 and Figure 4.42 show the speed (rad/sec) of the three generators, when the fault occurred at 1 sec the speed of each generator began to oscillate but due to presence of STATCOM the oscillations quickly damped out.

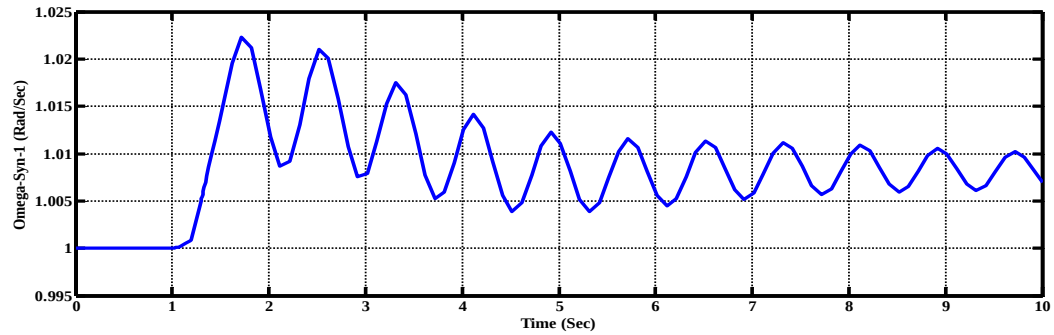


Figure 4.40 Speed variation of generator-1 with time considering STATCOM

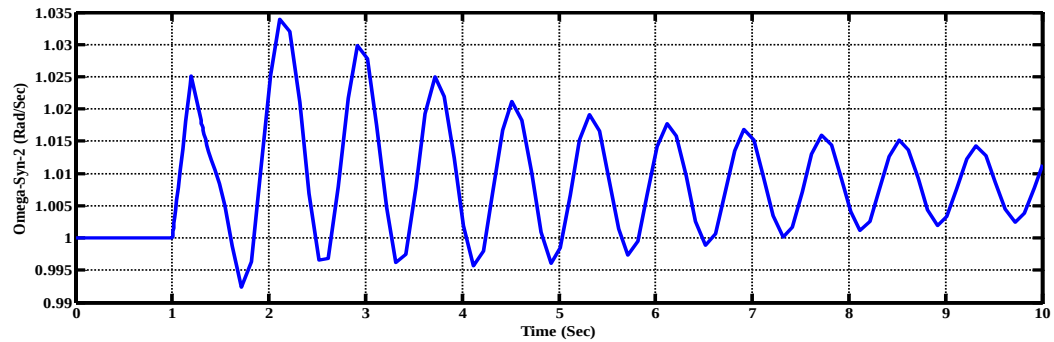


Figure 4.41 Speed variation of generator-2 with time considering STATCOM

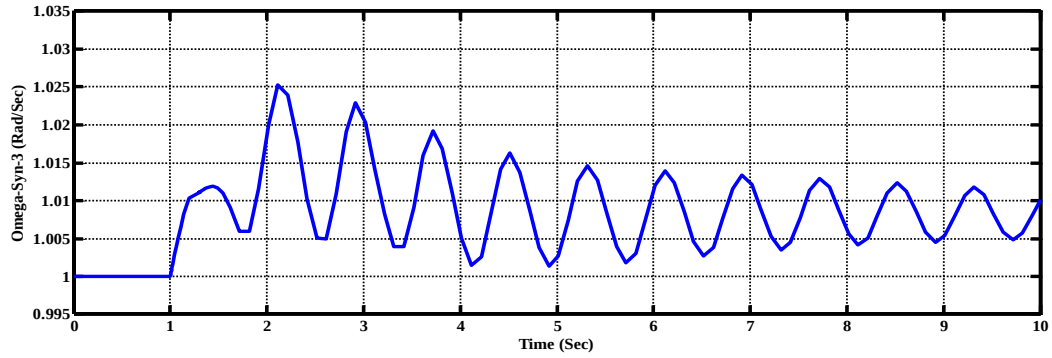


Figure 4.42 Speed variation of generator-3 with time considering STATCOM

Figure 4.43 shows the reactive current of STATCOM. It can be seen that STATCOM inject 1.2 pu reactive current to system to enhance the transient stability during the disturbance.

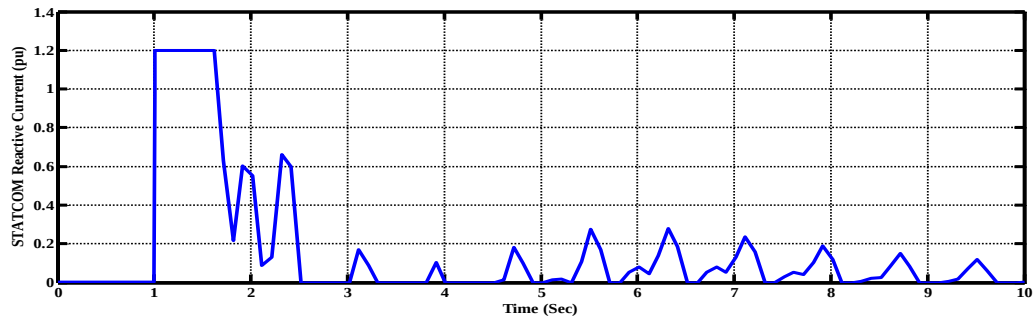


Figure 4.43 STATCOM reactive current

When the fault occurred at 1 sec the voltages V-Bus 1, V-Bus 7 and V-Bus 8 decreased to 0.8503 pu , 0.009819 pu and 0.2026 pu respectively after the fault is cleared the bus voltages recovered quickly as Figure 4.44, Figure 4.45 and Figure 4.46 illustrate.

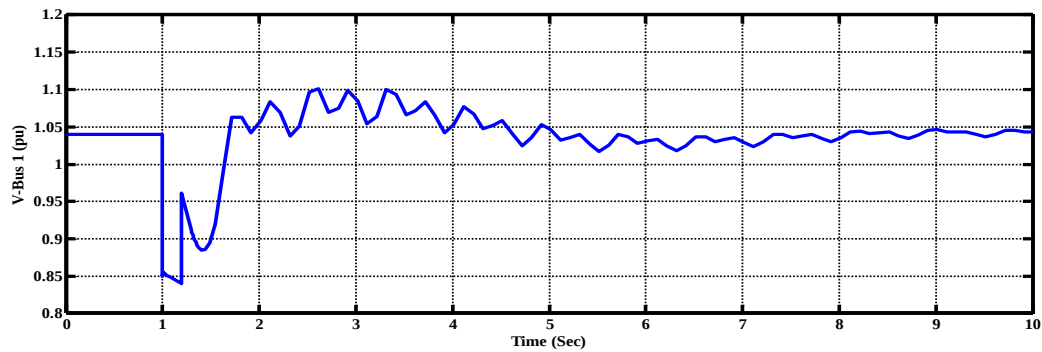


Figure 4.44 Voltage of Bus 1 with time considering STATCOM

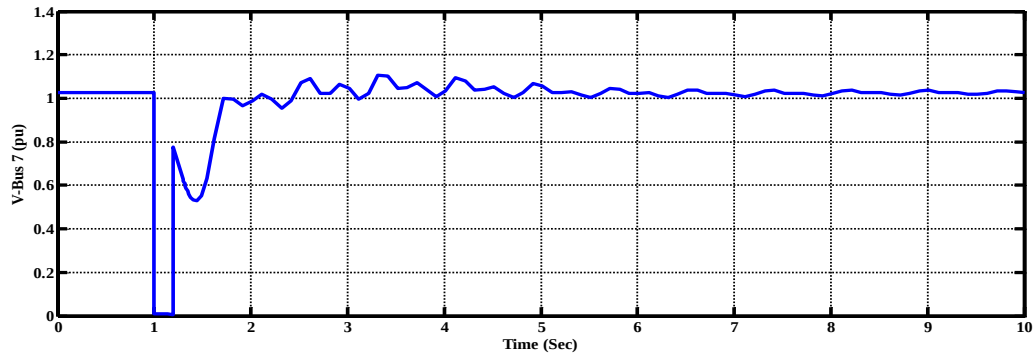


Figure 4.45 Voltage of Bus 7 with time considering STATCOM

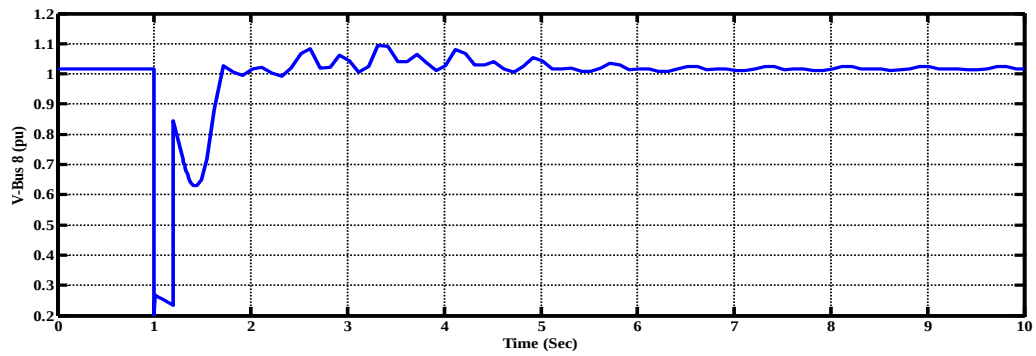


Figure 4.46 Voltage of Bus 8 with time considering STATCOM

Figure 4.47, Figure 4.48 and Figure 4.49 show the individual generator electrical and mechanical power for the system with FCT=0.2 sec. The results show that STATCOM is able to suppress the oscillations quickly.

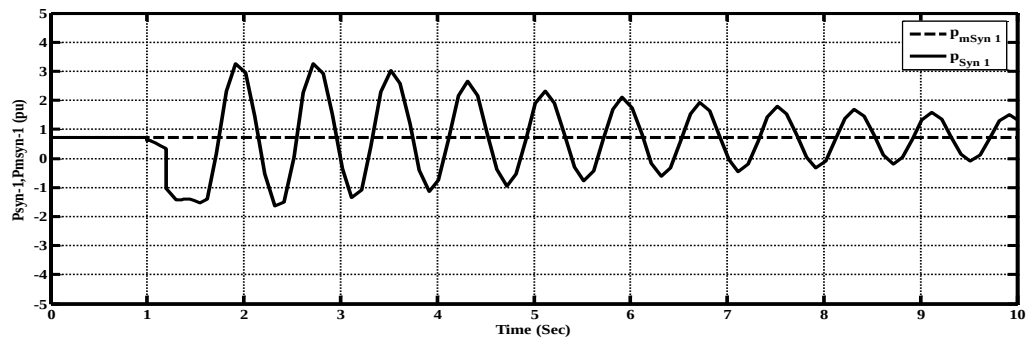


Figure 4.47 Electrical and mechanical power of generator-1 considering STATCOM

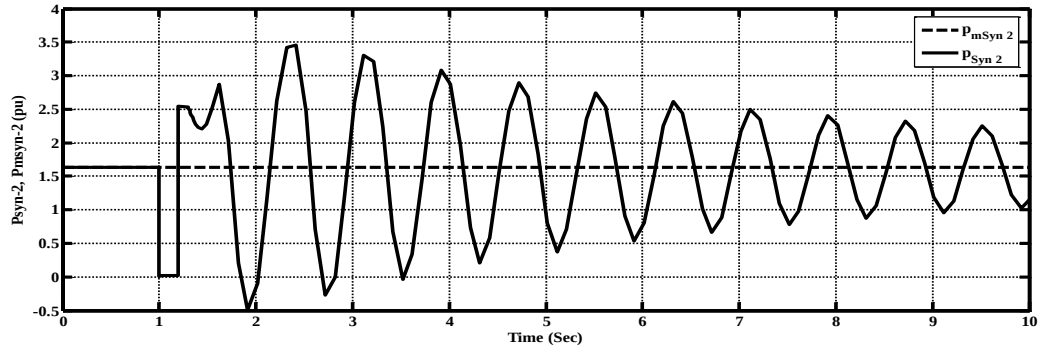


Figure 4.48 Electrical and mechanical power of generator-2 considering STATCOM

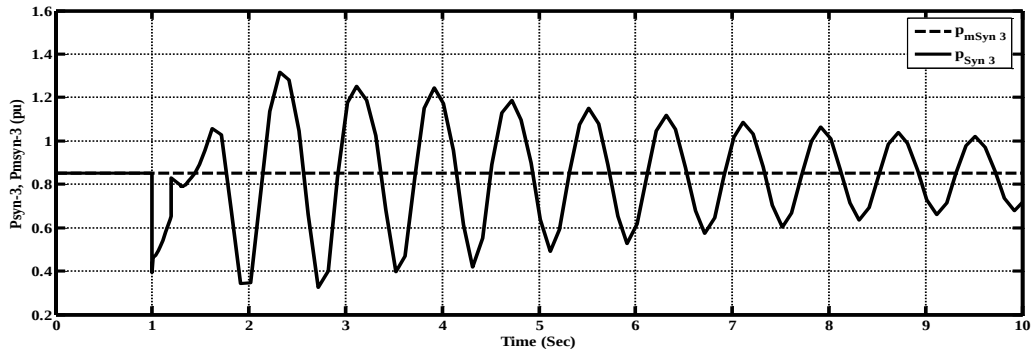


Figure 4.49 Electrical and mechanical power of generator-3 considering STATCOM

4.6 Summary

In this chapter the ability of STATCOM to maintain the transient stability has been investigated. Two machine system installed without STATCOM has been studied when a three phase fault occurred near bus 1 after that the effect of STATCOM in improvement of the transient stability has been studied by connecting STATCOM of 200MVA at midpoint of transmission line of the two machine system. Then the two machine system with step changing load is simulated in two steps without STATCOM and with STATCOM then the STATCOM damping characteristics have been analyzed. The study has been extended to multi-machine system and the popular IEEE 3-machine 9-bus system has been taken as case study. Firstly the system has been analyzed and the results has been discussed when a three phase fault occurred at bus 7 and the system installed without STATCOM. Secondly the system has been studied and the results has been discussed when STATCOM has been connected at bus 8 in the system.

Chapter Five

Conclusions and Recommendations

5.1 Conclusions

In this thesis, the effect of STATCOM for improving transient stability of two machine system under 3-phase fault installed without and with STATCOM is investigated. Simulation results indicate that without STATCOM the system became unstable, when STATCOM is implemented in the system, it became stable after the fault clearance. Also the two machine system installed with step changing load with and without STATCOM is studied, the results show that the STATCOM controller provides better damping characteristics as compared to the system without STATCOM controller. Also the effect of STATCOM for improving transient stability of multi-machine system under fault is investigated. The results indicate that the multi-machine system without STATCOM loss its stability but the presence of STATCOM provide stability to the system and good damping characteristics.

5.2 Recommendations

In the following, some recommendations are given for future research in this area :

- To use STATCOM for improving steady state stability in Sudan National Grid.
- To design Fuzzy-PI STATCOM controller for improving transient stability.
- To use STATCOM with fuzzy logic controller for damping oscillations of multi-machine power system.
- Application of STATCOM to increase transient stability of wind farm.

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APPENDICES

APPENDIX A

DATA OF TWO MACHINE SYSTEM

A.1 Generator Parameters :

$M1=1000 \text{ MVA}$, $M2=5000 \text{ MVA}$, $V=13.8\text{kV}$, $f=60 \text{ Hz}$, $X_d = 1.305$, $X'_d = 0.296$,
 $X''_d=0.252$, $X_q = 0.474$, $X''_q = 0.243$, $X = 0.18$, $H = 3.7$

A.2 Transformer Parameters :

$T1=1000 \text{ MVA}$, $T2=5000 \text{ MVA}$ $13.8/500 \text{ kV}$, $R_m = L_m = 500 \text{ ohm}$

A.3 Transmission Line Parameters Per km :

$R_1 = 0.01755\Omega$, $R_0 = 0.2758\Omega$, $L_1 = 0.8737\text{mH}$, $L_0 = 3.22\text{mH}$,
 $C_1 = 13.33\text{nF}$, $C_2 = 8.297\text{nF}$

A.4 STATCOM :

500kV , 200MVA , $V_{ref} = 1\text{pu}$, $T_s = 25 \times 10^{-6}$, $C_p = C_m = 3000 \times 10^{-6} \text{ F}$

APPENDIX B

DATA OF MULTI-MACHINE SYSTEM

B.1 Synchronous machine data

Specification of	Synchronous machine		
synchronous	Connected	Connected	Connected
Machine	to bus 1	to bus 2	to bus 3
Power rate	100	100	100
Voltage rate	16.5	18	13.8
R_a	0	0	0
X_1	0	0	0
X_d	0.146	0.8958	1.3125
X'_d	0.0608	0.1198	0.1813
X''_d	0	0	0
T'_{d0}	8.96	6	5.89
T''_{d0}	0	0	0
X_q	0.0969	0.8645	1.2578
X'_q	0.0969	0.1969	0.25
X''_q	0	0	0
T'_{q0}	0.310	0.5350	0.6
T''_{q0}	0	0	0
M=2H	2*23.64	12.80	6.02

B.2 Bus Data

Bus no.	Rating voltage (kV)
1	16.5
2	18.0
3	13.8
4	230
5	230
6	230
7	230
8	230
9	230

B.3 Load data

Load no.	Power (MVA)	Voltage rate (kV)	Active Power (pu)	Reactive Power (pu)
1	100	230	1.25	0.50
2	100	230	0.90	0.30
3	100	230	1.00	0.35

B.4 Transmission line data

Line No.	Power (MVA)	Voltage (kV)	R	X	B/2
1	100	230	0.0119	0.1008	0.1045
2	100	230	0.0085	0.0720	0.0745
3	100	230	0.0390	0.1700	0.1790
4	100	230	0.0320	0.1610	0.1530
5	100	230	0.0100	0.0850	0.0880
6	100	230	0.0170	0.0920	0.0790

B.5 Transformer data

Trans. No.	Power rate (MVA)	Primary Voltage	Secondary Voltage	R	X
In line 7	100	18.0	230	0	0.0625
In line 8	100	13.8	230	0	0.0586
In line 9	100	16.5	230	0	0.0576

B.6 Slack bus connected to bus 1

Slack bus connected to bus 1

Power rate (MVA)	100
Voltage rate (kV)	16.5
Voltage magnitude (p.u)	1.04
Reference phase (rad)	0

Qmax (p.u)	99
Qmin (p.u)	-99
Vmax (p.u)	1.1
Vmin (p.u)	0.9
Active power guess (p.u)	0.8