Transient Stability Improvisation in Power System by Utilizing the Concepts of UPFC, STATCOM and SSSC

[1]Muhammad Waqar, [2]Dr. N. Khan, [3]Muhammad Adnan, [4]Waqas Khalid, [5]Muhammad Rayyan Fazal
[123]Department of Electrical Engineering, COMSATS Institute of Information Technology Islamabad, Pakistan
[4]Department of Electrical Engineering, COMSATS Institute of Information Technology Abbottabad, Pakistan
[5]Department of Electrical Engineering, FAST-NUCES, Lahore, Pakistan
[1]waqar6414@gmail.com, [2]nasrullahk@comsats.edu.pk, [3]adnanalikhan1111@gmail.com, [4]asharab983@gmail.com,
[5]rayyan.fazal@tuf.edu.pk

Abstract— In the power grid system, the primary subjects are to transmit power with maximum power factor and high power quality, maximum transient stability, economical and minimum risk of system failure. The constantly increase of electrical power demands and loads, especially non-linear loads making the power system network become more complicate to operate and the system becomes unstable with large power flows without proper control and operation**.** The advancement in power system with time have brings new challenges and sometimes it is difficult to operate system in stable condition due to complex system network. However, on the other side there is vast progress been made in power electronics, which helps the power system to remain in stable condition during worst condition occurred due to fault? One of the invention of power electronics is FACTS technology. FACTS (Flexible Alternating Current Transmission Systems) devices are based on power electronics and other dynamic controllers that provide control of one or more AC transmission system parameters to enhance controllability and increase power transfer capability. One way to improve the power system control is by applying FACTS controllers such as STATCOM (Static Synchronous Compensator), SSSC (Static Synchronous Series Compensator) and UPFC (Unified Power Flow Controller). STATCOM and SSSC can be introduced to the power system to regulate terminal voltage and to improve power flow of system respectively but none of them can control the both parameters, while on the other hand UPFC can control voltage, impedance and phase at the same time. The FACTS devices (STATCOM, SSSC and UPFC) control scheme for the grid connected power system is simulated using MATLAB/PSAT in power system block set. By using IEEE 9 bus power system network, the effectiveness of STATCOM, SSSC and UPFC are tested by applying the 3-phase fault at different buses and evaluated the performance of FACTS devices in IEEE 9 bus power system during fault condition. The performance of STATCOM and SSSC is then compared with UPFC to obtain optimum solution to fault.

Index Terms— Unified Power Flow Controller (UPFC), Static Compensator (STATCOM), Static Synchronous Series Compensator (SSSC)

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1 INTRODUCTION

Due to a massive increase in needs of human being, the centralized power generation system faces a shortage of main energy sources (fossil fuels) as the demand is increasing day by day without an increase in alternative generation resources and transmission line capability. All these reasons may have stressed the power system to operate beyond the capability it is built to be handled originally [1]. This brings the major issue of transient stability of power system in concern. If some generators are operating very far from the load centers, then the problem of transient stability will lead to a major disturbance which can be a threat to the supply's security as well as grid operators will find it difficult for the daily operations of power system. Transient stability refers to maximum transfer of power through transmission line without losing stability due to large and sudden changes in the power network conditions such as 3-phase fault or loss of large generating/load units suddenly. Overloaded power system may show the non-linear behavior and the abnormal interaction among several power system units will result in different modes of oscillations. If there is no precaution taken on time to damp the oscillations, then these oscillations will effect the power flow and may even lead to the un-synchronization of generators which can cause the total or partial system shutdown. The abnormal response of system due to disturbances and the risk of losing synchronization among generators can be reduce by introducing the FACTS technology to power system. The significance of the implementation of FACTS devices to the grid will able to lead to energy efficiency and emission reduction. With the increase of the FACTS systems implementing to the grid, power quality and stability of the low to high voltage power transmission system is becoming a major area of concern [2].

The idea of Flexible AC Transmission system was proposed in 1995, which is then called as FACTS technology [3]. The main idea on which FACTS devices have been proposed to the world is to install the power electronics devices at the high-voltage transmission and distribution sides of the power grid in order to make the overall system controlled electronically. The advancement made in high power electronic semiconductor devices and control technology have achieved the invention of FACTS devices [4]. During the fault occurrence in power system, FACTS devices provides active and reactive power rapidly to the system in order to maintain the system stability and lower the transients of power generators. The power compensation provided by FACTS devices could maintain the voltage of the whole power system due to which power flow can be easily controlled.

Generally, FACTS devices can be categorized into two generations:

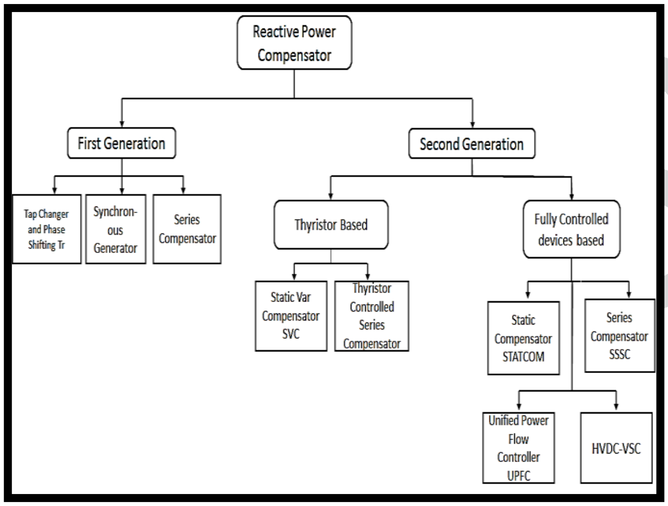

Figure 1.1: The category of FACTS devices [1]

First Generation FACTS devices: Fixed capacitance and dynamic devices are first generation of the FACTS technology. These first generation FACTS devices consists of tap changing and phase changing transformers, series capacitors and synchronous generators. These are all dynamics devices except the series capacitors which are also called capacitor bank. These devices are generally operated at the generation side of the power system but their cost is very high due to their extremely large size and maintenance. The big disadvantage of these devices is fixed series capacitors, since such devices are made up of several fixed-capacitance capacitors so these devices are very difficult to control to give the exact not-fixed input capacitance to the grid.

Second Generation FACTS devices: Static state compensator is the second generation of FACTS technology. It can be divided into two categories: thyristor-based technology and fully-controlled compensator based technology. The thyristor controlled device is half controlled device because once the device is on then it cannot be switched off manually until the main power is cut-off [5]. Static Var Compensator (SVC) and Thyristor-Controlled Series Capacitor (TCSC) devices belongs to this category [6]. While the fully controlled devices consist of Gate Turn-Off (GTO) thyristor i-e these devices can be manually switched on and off when needed. The Static Compensator (STATCOM), Solid Static Series Compensator (SSSC) and Unified Power Flow Controller (UPFC) belongs to fully-controlled devices. Unified Power Flow Controller (UPFC) is technically the most effective and versatile FACT device as it can perform the function of both STATCOM and SSSC at a time and it has transient stability improvement capability by handling the power flow on both sides of transmission line via shunt and series convertors. Hence our focus will be on UPFC in this research work [7].

Different FACTS devices play various roles in improving the stability of power system during disturbances. Some of their roles are discussed in the following table 1.1:

Table 1.1: Various Roles of Different FACTS devices [13]

Type	**Operation Problem**	**Corrective Action**	**FACTS Controllers**
Voltage Limits	Low voltage at heavy load	Supply reactive power	STATCOM, SVC
	High Voltage at low load	Absorb reactive power	STATCOM, SVC, TCR
Thermal Limits	Transmission circuit overloaded	Reduce overload	TCSC, SSSC, UPFC
	Tripping of parallel circuits	Limit circuit loading	TCSC, SSSC, UPFC
Loop flows	Parallel line load sharing	Adjust series reactance	SSSC, UPFC, TCSC
	Power flow direction reversal	Adjust phase angle	SSSC, UPFC
	Post-fault power flow sharing	Rearrange network	TCSC, SSSC, UPFC

1.2 Problem Statement

The increase in power demand and loads particularly non-linear loads, have stressed the power system to operate out of its capability for which it is built, makes the power system network more complicate to operate. This makes the system insecure due to large power flows without enough control. The large and uncontrollable power flow may also produce oscillations in power system due to which power generators will fallout of synchronization [1**]**. This may result in major loss of equipment and can costs us heavily. To overcome such faults and to damp oscillations we have to improve power system transient stability i-e to overcome such disturbances in minimum amount of duration. For such purpose FACTS devices are introduced in power system to improve power quality, power factor and transient stability. These advanced controllers based on power electronics are able to maintain voltage level and to increase transient stability by applying them at critical location of power system [3].

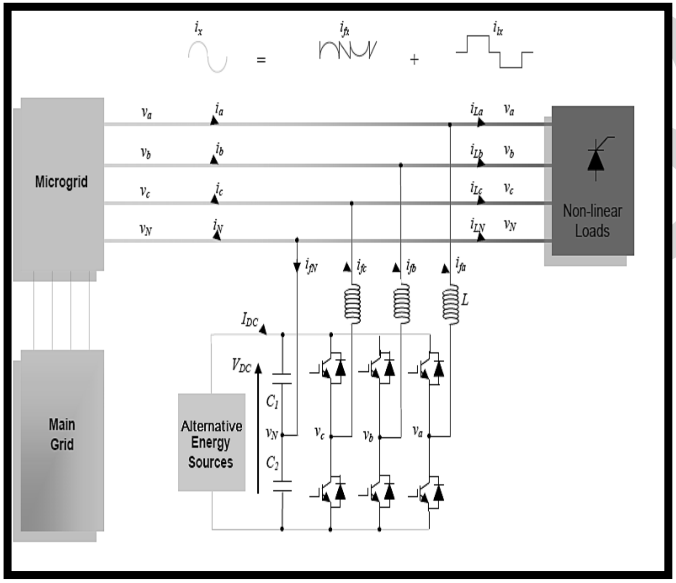

Fig 1.2: Example of Power System Topology [2]

1.3 Research Hypothesis:

Transient Stability plays a major role in power system security as it can affect the performance and whole cost of equipment and operation of other power system units. Higher the transient stability during disturbance, higher will be the performance and efficiency of power system, hence can provide sufficient saving of cost. Number of advantages could be gained if the transient stability of power system is improved as it can reduce power losses as well as prevent the system from extra cost by avoiding the disturbances in minimum possible duration of time. Transient stability improvement also reduces the electricity losses on distribution side and provide high voltage stabilization and excellent quality. In addition to this context, transient stability improvement increases the efficiency of power system equipment and lasts the equipment to operate for very long time which at the meantime decreases the costs of electricity. So FACTS devices should be researched to make our system more securable [2].

1.4 Research Objectives:

The scope of this research is to evaluate the enhancement capability of UPFC for transient stability by introducing a 3-phase fault in multi machine power system.

The research objectives are as follows:

i. Implementation of IEEE 3-machine nine bus power system model.
ii. To observe the performance of FACTS devices by implementing them at different buses and locations of power system.
iii. To observe the steady-state of implemented power system model during pre-fault condition without using FACTS devices.
iv. To study the power flow during transient state of power system under fault condition without using FACTS devices.
v. Transient stability analysis using FACTS devices during fault condition.
vi. Comparison of overcoming transient stability capability of UPFC with other FACTS devices.

1.5 Research Methodology:

The IEEE nine bus 3-machine power system is the proposed system which has to be tested for this research work. To achieve the objectives which are discussed above, the following tasks have to be carried out in several phases:

1.5.1 Phase-1: Analysis without FACTS

Implementation of IEEE nine-bus three machine power system using MATLAB. Transient Stability analysis will be performed during introduction of 3-phase fault to a bus or generator of power system without using FACTS devices in order to observe the system behavior during transients.

1.5.2 Phase-2: Analysis with STATCOM

Examining the improvement of Transient Stability of proposed power system using STATCOM (shunt controller). During disturbance the STATCOM will supply the voltage to maintain the voltage level of power system.

1.5.3 Phase-3: Analysis with SSSC

Examining the improvement of Transient Stability of proposed power system using SSSC (series controller). The SSSC will maintain the power flow of power system during fault condition and try to bring the system to its original position in minimum possible of time.

1.5.4 Phase-4: Analysis with UPFC

In this phase the Transient Stability improvement is examined using UPFC (combine shunt-series controller). The UPFC has combined functions of both STATCOM and SSSC, so it will operate according the type of disturbance occurred in the system.

1.5.5 Phase-5: Comparison of Results

Finally, the performance of STATCOM and SSSC will be compare with UPFC using the simulation graphs and will choose the best optimum solution to overcome transient Stability.

1.6 Significance of Research:

It is necessary for a power system operator to achieve a full control on transmitted power in a de-regulated electrical power sector. It is important as the load is increasing on daily basis as well as the variable nature of load which mainly attributes the non-linear behavior. The major effect of the non-linear behavior is the stability disturbance of system following a severe failure. To ensure the maximum power transfer by conventional means such PSS BR etc. are not close enough for modern power system due to their complexity. While the FACTS devices have been accounted for providing system operators with high flexibility of system parameters control to make sure that the maximum power is been delivered to the consumers [8]. In this thesis UPFC has to be investigated in reducing transient stability of proposed power system. The results which are going to achieve in this research can help the system operator in daily operations of power system as well as in future planning.

Literature Review

2.1 Introduction

In this chapter, the basic knowledge and principle of operation of FACTS devices have to be discussed. Moreover, it also includes the short overview of power flow study of system. The performance of FACTS devices is also being discussed to show how the system parameters are controlled for better system operation. Finally, a detail review of work related to this research is discussed.

2.2 Power Flow Study

Power flow study, also called a load flow study is a necessary technique includes a numerical analysis applied to a power system in order to calculate the load on each bus and generator. Usually a power flow study requires a modified notation such as per-unit method and one-line diagram, and concentrates on several parameters of AC power i.e. Voltage, voltage angle, real power, reactive power. It examines the load flow of power system during normal steady-state operation. There are number of software and tools available for power flow studies [9].

To continue with power flow study, often called the base case, there are many software implementations are available which performs different types of analysis for power flow such as short-circuit fault analysis, network stability studies (steady and transient-state) and by using the method of economic load dispatch and unit commitment analysis. A linear programming is used in some programs in order to calculate the best optimal power flow analysis. By best optimal power flow means the conditions which gives the lowest cost per kilowatt-hour transferred.

Power flow or load flow analysis for power system is necessary if there is a plan to expand the system in future as well as to determine the best way of operation for existing systems. The principle data which calculated from power flow study consists of magnitude and phase angle of voltage at each bus and transmission line and most probably the real and reactive power at each line.

Load flow analysis can be performed by using several computer software available that performs the simulation of actual operating steady-state condition of power system, enables the assessment of bus voltage profile as well as calculate the real and reactive power flow and losses. By performing load flow analysis using different ways of scenarios make sure that power system is sufficiently designed to meet the criteria of performance. A system which is properly and effectively designed may deliver the initial capital investment and future operating costs. Load flow studies are generally used to analyze:

i. The circuit or component loading
ii. The real and reactive power flow
iii. The proper transformer tap settings
iv. The bus voltage profiles
v. The power system losses

The purpose of load flow study is to acquire complete voltage magnitude and voltage angle information for each single bus of power system for concerned load and the real power and voltage conditions of generator. Once the above data is calculated, the real and reactive power flow through each single transmission line pf power system as well as the output reactive power of generator can be determined.

Due to the problem of non-linear nature of power system, numerical analysis is applied to find out the solution which is in acceptable tolerance limit. The approach to reach to the solution of finding the way out of power flow problem is initiates with finding the known and unknown parameters in the system. The known and unknown parameters are relying upon the type of bus. A bus to which none of generators of power system are connected, is called a Load Bus. But exceptional situation for the bus to which at least one generator connected to it, is called Generator Bus. This exception is applicable to only one arbitrarily chosen bus that has generator connected to it. This bus is referred as the Slack Bus [10].

To evaluate the effeteness of STATCOM, SSSC and UPFC in controlling the system voltage, power flow study is important. Furthermore, during planning stage, repetition of power flow studies is required to obtain the ratings of SSSC, STATCOM and UPFC among others. Therefore, power flow studies are certainly one of the most essential studies requires to be carried out before applying any of FACT device such as STATCOM, SSSC and UPFC to the power system [11].

2.3 Introduction to FACTS Controllers

The concept of Flexible AC Transmission System (FACTS) is based on power electronics which offers the effective control of one or more AC transmission parameters to boost controllability and improve the power transfer capability. There are three types of FACTS devices which are categorize as series, shunt and combined shunt-series controllers.

The shunt type of FACTS controller is very efficient in improving the voltage profile of a specified bus, increase the power damping oscillation and improve the transient stability of system during disturbance. Some of examples of shunt type of FACTS controllers are Static VAR Compensator (SVC) and Static Synchronous Compensator (STATCOM).

The series type of FACTS controller is useful in increasing the voltage stability limit, improves the transient stability margin, helps in increases the power oscillation damping and sub synchronous oscillation damping of power system during disturbance. Examples of series type of FACTS controllers are Thyristor Controlled Series Capacitor (TCSC), Thyristor Switch Series Capacitor (TSSC) and Static Series Synchronous Capacitor (SSSC).

The combined shunt-series type of FACTS controller offers multi-functional capability at a time due to which several problems have overcome facing by power industry. Some of example of shunt-series type of FACTS devices are Unified Power Flow Controller (UPFC) and Interline Power Flow Controller (IPFC) [3].

2.3.1 Theory of FACTS Controllers

The shunt type pf FACTS devices operates on the basic principle of steady state transfer of power and the voltage level across the transmission line can be controlled by proper reactive shunt compensation. While connected to the power system, capacitors generate reactive power while reactors (or inductors) absorbs, depends on the need of the power system. For effective operation of shunt controller, mechanical switches are used with VAR generator and absorber to control the reactive power generation and absorption [3]. Actually the shunt connected FACTS controllers are divided into three types which are as follow:

i. Variable impedance or reactance to be exact type.
ii. Hybrid type.
iii. Switching convertor type.

The series type FACTS devices operates on the basic principle of the elimination of exceeded portion of the reactive line impedance which can gradually increase the rate of transfer of power. This is because of the reason that transmission of AC power over a very long transmission line is mostly limited by the series reactive impedances of line. So the main role of series capacitive compensation is basically to minimize the overall actual series transmission impedance i-e from sending end point to receiving end point of the transmission line.

The series connected FACTS devices are further divided into two types, namely as switching convertor type series compensator and the variable impedance type series compensator device. The major principles of series type of FACTS controllers are much similar to that of shunt connected FACTS controllers, the only difference between them is the compensator i-e series compensator is reciprocal of shunt compensator.

The combined shunt-series type of FACTS controllers have the capability of major functions of both shunt and series connected FACTS controllers. It is capable of handling, simultaneously or one by one, all those major parameters and variables which have a great effect on power flow in transmission line such as voltage, impedance and phase angle [12].

2.3.2 Operation and Control of FACT Controller

All types of FACTS controllers based on convertor which is known as Voltage Source Convertor (VSC). A basic building block circuit of any voltage source convertor VSC is exactly same as three phase Convertor Bridge. The most common known configuration of a three phase bridge circuit is shown in Figure 2.1. The basic three phase bridge convertor consists of two DC terminals which are showed by plus '+' and negative '- 'sign in the below given figure 2.1. There are three AC terminals '~' which are connected at the mid of bridge convertor legs. By controlling the different states of switches connected to the legs of bridge, a random series of voltage waveforms at the AC terminals can be produced.

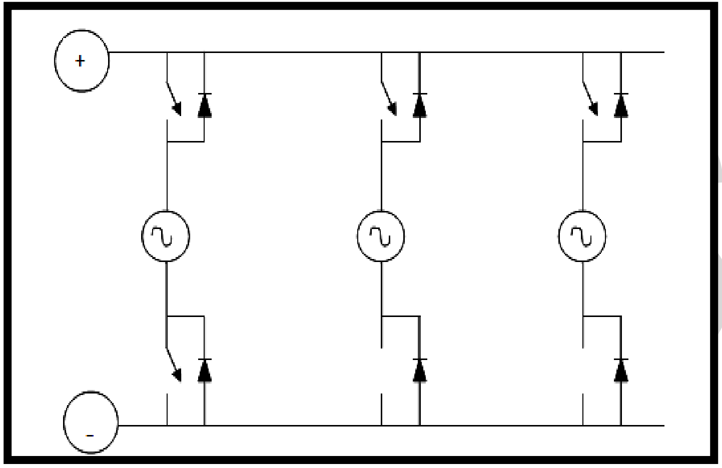

Figure 2.1: Three Phase Convertor Bridge (Basic Building Block of Voltage Source Convertor) [13]

When a voltage source convertor VSC is connected to a transmission system then it has to use the transmission line frequency for its operation in order to generate a stable set of sinusoidal waveforms of voltage. Thus, a VSC connected to the transmission system has got only two options of operation, it can fluctuate the magnitude and phase angle of its output voltage according to the system voltage. [13]

These two control strategies of choice can be followed simultaneously to exchange the reactive and active power with the transmission system. The magnitude of reactive power, exchanged with transmission system is limited only due to the current amount of the convertor switches. While on the other hand active power linked to (from) the transmission line has to be provided from (delivered to) the DC terminals, as symbolically represented in figure 2.2 [13].

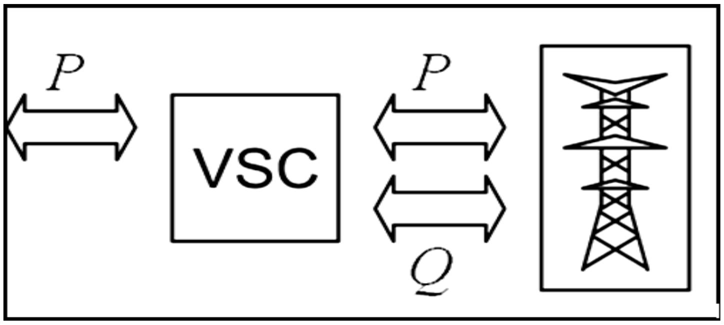

Figure **2.2: A VSC connected to the transmission line- P and Q exchange [13]**

2.4 Introduction to STATCOM

STATCOM, the Static Synchronous Compensator) or also known as ASVG, the Advanced Static Var Generator) is a solid state voltage source convertor that is linked with a transformer and coupled in parallel to a transmission line. An almost sinusoidal form of current is injected by STATCOM of variable amplitude to the point of connection. Its depend upon the concept that a controllable AC voltage source has to be generated by voltage source invertor just before a transformer leakage reactance so that the voltage across reactance generates and enables the exchange of active and reactive power between the STATCOM and transmission system. The efficiency of STATCOM is rely upon its capability of regulating the reactive power flow through it which is further useful for regulation of transmission line voltage [14, 15, 17].

2.4.1 Function of STATCOM:

A STATCOM consists of a DC to AC voltage source convertor along with a power storage bank, generally a DC capacitor. The function of a STATCOM is that it operates as a controlled Source of Synchronous Voltage (SSV) while linked to the transmission line through a coupled transformer as shown in figure 2.3[14, 17].

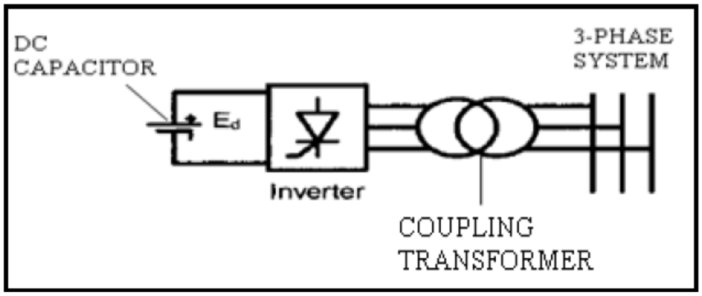

Figure: 2.3 Schematic Configuration of STATCOM [13]

The STATCOM is a shunt reactive power compensating electronic device which produces AC voltage and inject it to the transmission line, which in-turn generates a current of variable amplitude at the connection point. This injected current is nearly out of phase about 90 degrees with the line voltage, therefore matching a capacitive or an inductive reactance at the connection's point with the transmission line. The operation of STATCOM model is testified by allowing the reactive current pass through it. It will be very convenient to absorb and generate the reactive power in order to regulate the line voltage of the concerned bus to which STATCOM is connected [15 16, 18].

2.4.2 Operation of STATCOM

The operation of control of reactive power through STATCOM is a well-known technique for improving transient stability of power system. The operation of STATCOM involves the exchangeable amount of reactive power (capacitive or inductive) between the power system and STATCOM, can be adjusted or set by monitoring the output voltage of STATCOM with respect to the voltage of system. The STATCOM will supply the reactive power, when Q is positive with respect to the system and STATCOM will absorbs reactive power from system when Q is negative. The generation of reactive power is being achieved through charging and discharging of the energy bank capacitor [14, 15, and 16]. The reactive power deliver by the STATCOM to system can be represented by the following given equation:

$$\boxed{Q = \frac{V_{STATCOM} - V_S}{X} V_S}$$

Where:

Q = Reactive power deliver by STATCOM

$V_{STATCOM}$ = Amplitude of STATCOM output voltage

V_s = Amplitude of System voltage

X = Equivalent Reactance between the system and STATCOM

The simplified diagram of STATCOM is represented in figure 2.4, it shows the STATCOM with an inverter voltage source E along with a tie reactance X_{tie}, linked to an ac system through voltage source V_{th} and Thevenin reactance X_{th}. The STATCOM will show inductive reactance behavior connected at its terminal, when convertor voltage is higher than system voltage. Therefore, the system gets the STATCOM's behavior as a capacitive reactance and STATCOM is functioning in capacitive way. The current flows to the AC system through STATCOM, and the controller generates reactive power. In this scenario, the system absorbs capacitive current that is 90 degrees out of phase from system voltage, taking in consider that the convertor losses almost equal to zero [18, 19].

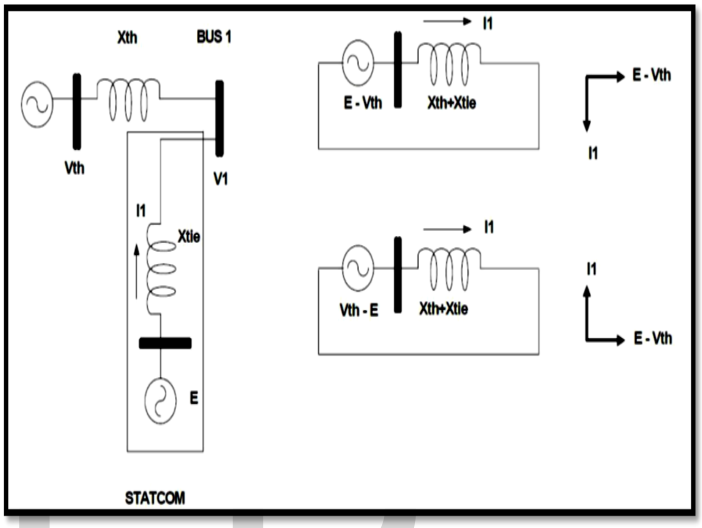

Figure 2.4: Simplified Diagram of STATCOM [17]

2.4.3 Circuit Configuration of STATCOM

STATCOM can be represented into two types of circuit configurations, one of which is multi-level convertor while second one is multi-pulse convertor. Both types of STATCOM possess different operation and different connection.

In the configuration of multi-level, there are three more different convertors configurations with in it, one of which is Diode-clamped convertor, the second one is flying capacitor convertor and third one is Cascade convertor. A cascade convertor consists of standard form of H-bridge in series. As compared to other two configurations, cascade convertor design is economical than clamping diode convertor and flying capacitor or zigzag transformer. As it requires least amount of component used within it and low costs spend on its circuit designing. There are large dc side capacitors required in cascade convertor compared to the flying capacitor and clamping diode during balanced condition but I can offer separate voltage control to overcome high unbalancing of voltage. [17, 20, 21] Figure 2.5 shows the configuration of cascade convertor (multi-level convertor).

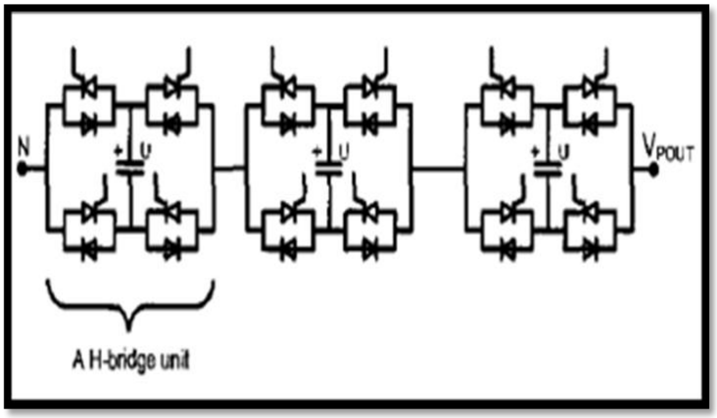

Figure 2.5: Cascade multilevel convertor configuration [21]

In multi-pulse convertor configuration, there are 3-phase bridges connected to DC side of convertor in parallel, as shown in Fig 2.6. The bridges are magnetically connected through the zigzag transformer. The configuration of convertor is being ended up in a way that the arrangement of transformer makes the 3-phase bridges to be appear in series if viewed from the AC side of convertor. Each and every windings of transformer have been phase shifted in order to cancel the desired harmonics and to generate a multi-pulse output voltage. On the other hand, if to improve the harmonics content and reduce the fundamental of var rating, but at the cost of higher snubber and switching loss, a pulse width modulation (PWM) is applied to the convertor [20, 21].

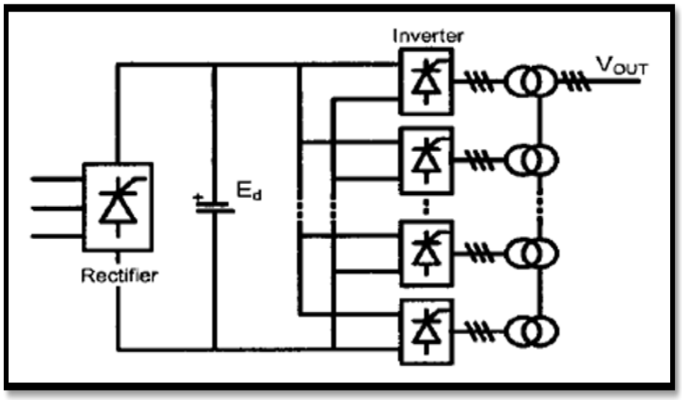

Figure 2.6: Configuration of multi-pulse convertor [21]

2.4.4 Applications of STATCOM

There are several advantages of STATCOM over the traditional compensators. The applications and advantages of STATCOM can be briefed as:

i. It has a short duration of overload capability which is 20%.

ii. It can perform the function of voltage source to support other convertor based controllers.

iii. It can operate smoothly with different types of compensators.

iv. There is no requirement of large filter in STATCOM.

v. To deliver the same performance level as compared to SVC, it requires 15-35% less MVA power rating than SVC for the steady state power transfer of system, support of dynamic voltages and performance of transient stability.

The other advantages of STATCOM includes that it has a dynamic performance far better than other traditional var compensators. The maximum system response time of STATCOM could reach to 10ms or less of it. STATCOM has the capability to keep the maximum level of capacitive output current at very low system voltage, which makes the STATCOM much more effective in improving the transient stability than SVC and other compensators.

With compare to other compensators, STATCOM bears a flexibility in redundancy of design, which makes it highly reliable controller. Moreover, STATCOM has a small size and cover a very less space as compared to other compensators [22].

2.5 Introduction to SSSC

The model of Static Series Synchronous Compensator (SSSC) is design in a way that it can connect in series with the transmission line as shown in Figure: 2.3. The SSSC consists of a voltage source convertors (VSC), a coupling transformer through which SSSC links to transmission line, a magnetic interface and energy storage DC capacitor, connected to a secondary side of coupling transformer. The coupling transformer is coupled in series to the transmission line and injects the voltage with 90-degree phase difference to line current, into the transmission line.

The function of magnetic interface is to provide the multi-phase voltage pattern in order to avoid the low order harmonics. The voltage V_s which is injected by SSSC to line through coupling transformer is perpendicular to the line current I_L [9, 13].

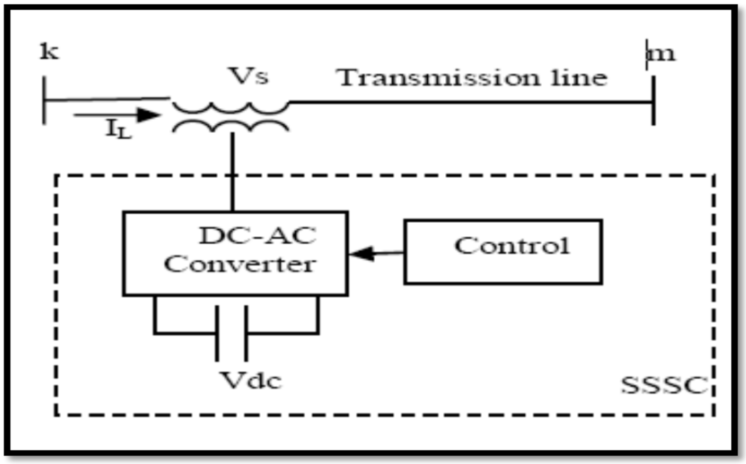

Figure: 2.7 Configuration of SSSC with transmission line [13]

Principally the SSSC is a synchronous voltage source connected in series with transmission line to provide a line compensation during unwanted conditions occurred in power system. This specific control technique of SSSC is achieved by handling an interface between DC voltage source (generally a capacitor) and the AC power system. The series capacitive compensation is basically used to provide the maximum compensation to the transmission line in order to reduce the average effective series impedance from sending to receiving end. A relationship is defined which characterizes the transmission of power over a single is given below:

$$\boxed{P = \frac{V^2}{X} \sin\delta}$$

Where:

P = Real transmission power flow over single line

V = The sending end and receiving end voltage (assume Vs = V_R = V)

X = Equivalent line impedance

δ = Power angle

SSSC is powerful controller, once it connected in series with transmission line, it injects a voltage in quadrature with the transmission line current in order to provide the series capacitive or inductive reactance to transmission line according to the requirement of power system. A SSSC comes with energy storage system (dc capacitor) and bears an absorbing capability of power to exchange the real power with system [9, 13, and 23].

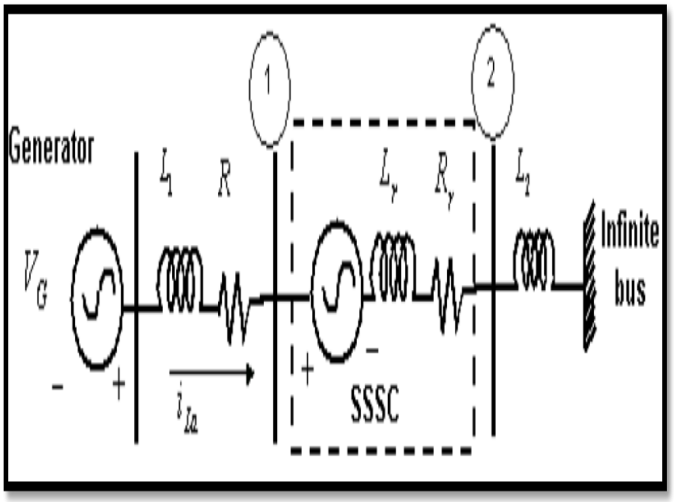

Figure: 2.8 One-line diagram of SSSC [23]

During disturbance in power system, the exchange of reactive power is handled by the magnitude of injected voltage to the overloaded transmission line while a regulation of active power is achieved by controlling the power angle. The injected voltage phase angle is used to set the inductive or capacitive mode of operation with respect to the need of transmission line. When injected voltage is lagging the line current, reactive power is delivered to line by SSSC and it operates in capacitive mode while on the other hand if injected voltage is leading the line current, reactive power is absorbed from line and SSSC is operating in inductive mode [23].

In above one-line diagram of SSSC integrated system, the SSSC configured of voltage source and equivalent impedance (L_r and R_r). The SSSC is connected between bus 1 and bus 2 of proposed power system. The combination of L_1 and R represents the line while L_2 represents the coupling transformer [23].

2.5.1 Function of SSSC

SSSC is basically used to control the real power flow in transmission line and this is the main function of SSSC. This task can be achieved by two control strategies either by controlling of line current directly or by alternate controlling of the compensative impedance X_s or compensative voltage V_c indirectly (). The advantage to control the direct power flow is to maintain the transmitted power in a closed loop mode which is being determined by the reference. But on the other hand, due complex network of power system the maintenance of uniform flow of power may not be desirable or even it will be impossible in such condition. So therefore, in some operations the control of impedance (or voltage), which maintains the impedance feature of line, may be choose as a preferred control strategy from the operating standpoint. The relation of series impedance S, is generally represent as the ratio of the injection of reactance in series X_s to the reactance of line X_L i-e $S = X_s/X_L$. Hence for capacitive series compensation the series reactance of line is $X_{Line} = X_L - X_s$, where $X_s = X_L$ x S.

Likewise, the inductive series compensation relation for the series reactance of line expressed as $X_{Line} = X_L + X_s$, where $X_s = X_L$ x S. The main purpose of the control system is to maintain and keep the voltage of SSSC, V_c is in quadrature with line current I_L and also to maintain the amplitude of voltage V_c to a controlled level in order to achieve the requirement of compensation, which is the need of series compensation [23, 24].

2.5.2 Operation of SSSC

The control topology of SSSC is shown in Fig. 2.9. The phase angle of line current is represented by principal synchronization signal θ. The impedance which is injected by the SSSC is expressed as the ratio of voltage of q-axis V_{eq} of the SSSC to the line current I_L. This impedance is there after compared with the reference of impedance compensation S x X_L.

In order to charge or discharge dc capacitor of SSSC, a PI controller produces the required amount of phase displacement Δα. A negative Δα shows that the real power flow is transmitted from power system to the SSSC, hence charged the dc capacitor while the positive Δα will lead to the discharging of dc capacitor. In the same manner, reference reactance X_{ref} is negative then voltage V_c lags the line current I_L by 90 degrees plus Δα (capacitive compensation) and if X_{ref} is positive then voltage V_c leads the line current I_L by 90 degrees plus Δα (inductive compensation). The end output of control system of SSSC is the phase angle θ of the output.

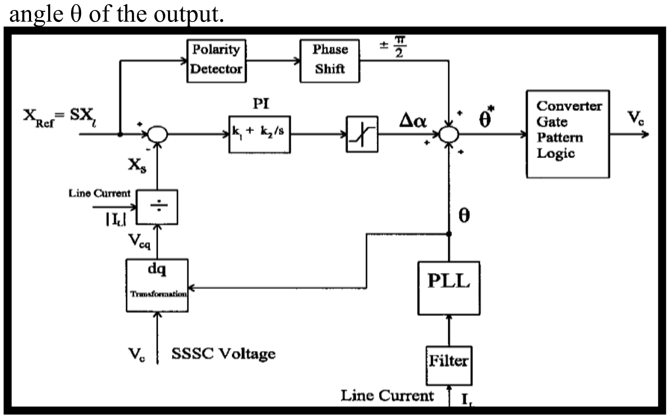

Fig: 2.9 Control configuration of SSSC [23]

Generally, SSSC generates a sinusoidal voltage at its output terminals within considerable range of magnitude and almost in quadrature with the transmission line current. This sinusoidal voltage is injected into transmission to produce either an inductive or a capacitive reactance which is in series with transmission line to decrease or increase the overall reactance of transmission line accordingly.

Hence, the power flow will vary in the transmission line due to change in overall reactance. Therefore, the SSSC is intended to be one of powerful FACTS device as it controls the impedance of transmission line which is independent of line current and because of this operation, power flow is controlled effectively. As a matter of fact, the magnitude of injected voltage to the transmission line by SSSC helps in controlling the exchange of reactive power while on the other hand, the control of phase angle is used to regulate the active power exchange [23, 24].

2.5.3 Advantages of SSSC

The SSSC is commonly used to level the voltage of power system during disturbances and try to bring the voltage to its original level. Apart of this, SSSC consists of several advantages during steady state conditions, some of them are briefed below: [25].

i. Helps in power flow control of system during normal conditions.
ii. It can also help to manage the reactive and capacitive power requirement.
iii. In interconnected distribution networks the load balancing is a major problem, SSSC can minimize it effectively.
iv. With the help active filtering it reduces the harmonic distortion.
v. SSSC helps in improvement of power factor by the continuous injection of voltage or in combination with well configured controller.

2.6 Introduction to UPFC

Unified Power Flow Controller (UPFC) is a power electronic based controller which provides fast and quick reactive power compensation response at high voltage level electric transmission systems during disturbances. There is a pair of three phase controlled bridges is implemented in UPFC which generates an AC current. This AC current is injected to the transmission line with the help of series transformer. Following the injection of AC current to transmission line, it can improve the active and reactive power flow in the transmission line. The UPFC comprises of solid state power electronics devices such GTO, IGBT etc, which offers multipurpose flexibility to the power system while the conventional control systems based on thyristors which do not offer such flexibility.

The UPFC idea was invented by L. Gyugyi in 1995. The UPFC is a combined FACT technology of a static synchronous series compensator (SSS) and a static synchronous compensator (STATCOM) connected through the common DC voltage link (a capacitor). UPFC performs a secondary but a very significant function which is stability control of power system in order to damp the unwanted system oscillations in order to improve transient stability of power system [13, 26].

2.6.1 Function of UPFC

Unified Power Flow Controller (UPFC) is a versatile controller and is known for simulating a multiple function at a time, it maintains the power flow level throughout the transmission lines of power system by controlling the voltage magnitude. UPFC can perform a leading role in the steady and dynamic operations powers system networks as it can provide a several advantages during such operations. With the invention of UPFC, new challenges have been aroused in power electronics and designing of power systems. The main configuration of UPFC consists of two voltage source convertors (VSC), out of which one convertor is connected in series with transmission line (coupled with SSSC) while the other one is connected in parallel with transmission line (coupled with STATCOM).

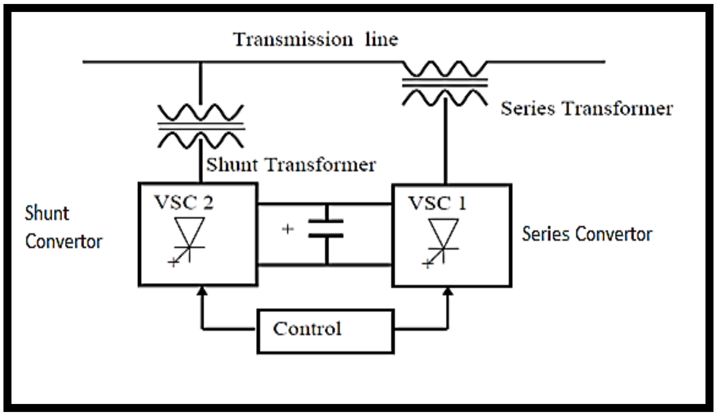

Figure: 2.10 Simplified Configuration of UPFC [13]

The UPFC is designed for the dynamic compensation as well as for the real time control of power flow in AC transmission lines and power systems. It offers multifunctional flexibility which is certainly required by the power system operators to come up with many problems. With the comparison to the conventional power transmission technology, the UPFC is capable to control, either selectively or simultaneously, all those parameters which directly lay effect on power flow in the transmission line (i-e impedance, voltage and phase angle) and this major role makes it unique and powerful than other FACTS devices. It endures the capability of controlling both reactive and active power in the transmission line independently. The UPFC is not only used to play the role of different controllers and regulators such as STATCOM, TCSC, SSSC, and phase angle shift regulator but also offer other multipurpose flexibilities by combining the different functions of these controllers.

Unified Power Flow Controller (UPFC) is comprises of two voltage source convertors (VSC) along with power electronic switches such as GTO's or IGBT's, and these two VSC's share a common DC circuit charged by DC capacitor storage, for their operation. This configuration makes the convertor to functions as an ideal ac to ac invertor due to which the real power can flow without any restriction in either direction, between the AC terminals of both convertors and each convertor can absorb or generate reactive power at its own AC output terminal, independently [13, 26, 27].

2.6.2 Operation of UPFC

The principle function of UPFC is performed by invertor 2 of the controller, as it injects the ac voltage V_{pq} with considerable magnitude V_{pq} i-e $0 \leq V_{pq} \leq V_{pqmax}$ and with a phase angle θ i-e $0 \leq \theta \leq 360$, at the nominal power frequency, in series to the transmission line through a coupled transformer. The injected voltage by invertor 2 of UPFC is considered as a synchronous voltage source for the transmission line. The flow of current in transmission line is made possible due to this voltage source which results in exchange of real and reactive power between the line and AC power system [28].

The invertor transforms the real power which is exchanged at the ac terminal i-e at the terminals of coupled transformer, into DC power that is transfer to the dc link as a positive or negative real power in order to charge the DC capacitor. The reactive power which is exchanged at the terminals of ac system, is basically generated by the invertor internally.

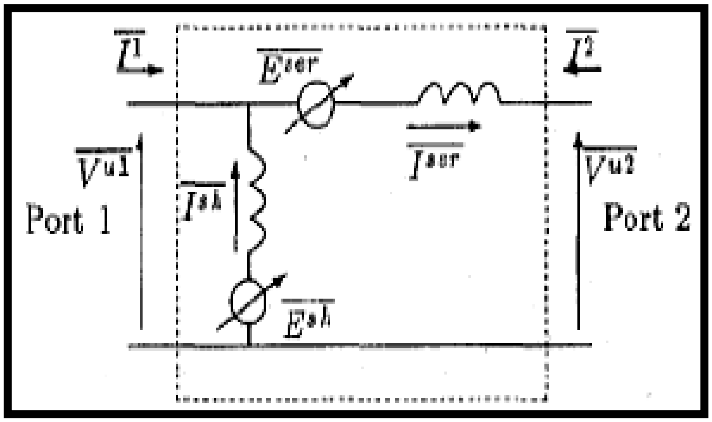

Figure 2.11: Representation of UPFC as 2 port device [23]

The major function of invertor 1 is to deliver or absorb the real power which is required by the invertor 2 at the shared dc link. The power stored in dc link is transformed back into to ac power and injects to the transmission line by the means of coupled shunt transformer. Invertor 1 has also the capability to generate or absorb the reactive power if required, and therefore independent shunt reactive compensation is provided by invertor 1 for the transmission line. It is necessary to consider the situation, that if there is a closed or direct path for the flow of real power, formed by the action of series injection of voltage back to the transmission line through the operation of invertor 1 and 2, then the equivalent exchange of reactive power is absorbed or delivered locally by invertor 2 and hence there is no reactive power flow occur through the transmission line.

It is therefore invertor 1 can be operated at a unity power factor and has the capability of exchanging reactive power with the transmission line independent of the exchange of reactive power by the invertor 2. It is clear then that there is continuous flow of reactive power through UPFC [28, 29].

2.7 Previous Studies and Research on FACTS Devices

A Journal published by Prechanon Kumkratug in 2011 on improving the transient stability of power system using SSSC. In this journal the author has discussed the complications of transmission line networks which carries heavy load due to requirement of today’s modern world. Hence such heavy loads can cause the stability problems to the system. Now a days the major interest of power systems is to improve the transient stability during disturbance. In this research journal SSSC is applied to power system to improve transient stability. In order to verify the effectiveness of SSSC on transient stability improvement, the author have done some tests on modified single machine infinite bus system have carried out. The system consists of one generator, a transformer connected to the series of infinite bus system. Based on the journal paper, the author has carried out the continuous power flow analysis in order to calculate the maximum power transfer capability without the implementation of SSSC. With the means of this analysis, the total generation of power from generator, the maximum loaded parameters and power flow load on each bus is analyzed. It was found out from the above calculation that the bus m, connecting two pair of lines was being congested and overloaded. With the determination of overloaded and congested bus, the researcher eventually determined the exact place for the implementation of SSSC in system. After the insertion of SSSC in series with the overloaded bus, the author once again analyzed the power flow of power system and after analysis the total generation of power from generator, the maximum loaded parameters and power flow load on each bus is calculated again. Now by having the power flow results of before and after the insertion of SSSC in system, a comparison had been made between the two different power flow data’s which concluded that the power transfer capability is high increased after the insertion of SSSC in series to the overloaded bus and relief the bus from extra load. Hence SSSC has the capability of improving transient stability [30].

Arvind. P (2012) did a research on STATCOM to improve the transient stability of power system. A typical two machine transmission system with 230kv transmission line is used for the calibration of performance of STATCOM. A detailed power flow study had been done in order to determine the weak bus by calculating the voltage profiles data of each bus in the proposed system. So the bus with the worst voltage profile (lowest voltage compared to other buses) had been chosen for the treatment with STATCOM. Therefore, STATCOM is connected in parallel to the selected bus and once again a detail continuous power flow study had been applied to the system in order to obtain the voltage profiles. After the comparison of before and after the result of power flow analysis, it was concluded that the voltage stability of overall power system has been increased due to the insertion of STATCOM and the bus with the worst voltage profile had been relieved [31].

R. Kr. Ahuja (2012) studied and evaluated the performance of UPFC to improve the transient stability of power system. The author proposed a 11 bus system to study the detailed performance of UPFC, in which bus no. 3 is selected as slack buck which keeps its voltage at 1 p.u while fault is injected at bus 8 in 1 sec and kept he fault clearance time at 1.05 sec. A detailed power flow study of proposed had been carried to analyze the performance of system during fault without using UPFC. The generators were fallout of synchronization due disturbance and bus 8 experienced as a worst bus voltage when fault is injected to it. After this evaluation, UPFC is inserted in between bus 8 where fault is injected, and bus 9. Now the voltage profiles of all buses had been evaluated and studied as well as the profiles rotor angles of each generator and these result were then compared with the previous results of power flow study without using any FACT controller. It was found out that without using UPFC the rotor angle of generator had been increasing which made the generator to fallout of synchronization while with UPFC they remain in synchronization. Similarly, the voltage profile of each bus had been improved with UPFC due which the transient stability of power system is certainly improved [32].

Research Material and Methods

3.1 Introduction:

This chapter discussed about the methodology approach in simulating the 9-bus test system with FACTS controllers (STATCOM, SSSC and UPFC) using MATLAB Sim Power System Toolbox software. This software can make analysis of load flow more accurate and easily. Before the performance and the effect of FACTS controllers in power system were evaluated, firstly the location or the placement of the FACTS controllers it selves was determined. In realizing this, an analysis named Power Flow analysis was used in order to determine the weak bus and the underutilized line, and hence determine the location of FACTS controllers in the system.

3.2 IEEE 9-Bus Test System

The data of test system apply in the project are from IEEE test system. For this project, the test systems have been used are 9-bus test systems. The single line diagram of the 9-bus test system is shown in Figure 3.1.

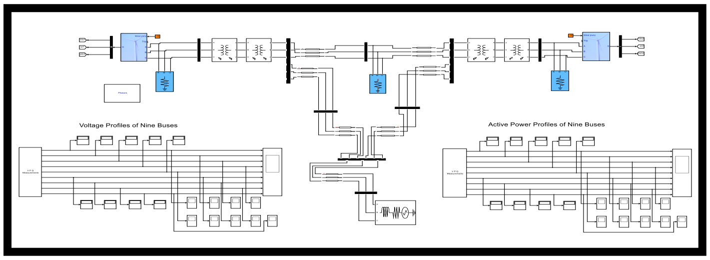

Figure 3.1 IEEE 9 bus system

The proposed IEEE 9 bus system consists two wind generators which are connected to the transformers through bus 02 and bus 03 respectively. An equivalent load is connected to bus 01 at the other side of power system. The other three loads are connected with wind generator 1, wind generator 2 and with bus 08, respectively. There are four transformers of nominal ratings are used in power system, two of which are connected in between bus 02 and bus 07 while the other two are connected in between bus 03 and bus 09 [33]. The ratings of different equipment used in proposed power system is tabulated in table 3.1:

Table 3.1: Test System details

S.No	TEST SYSTEM DETAILS		
1	Generators	Wind Turbine 1 Wind Turbine 2	1000 MW 1000 MW
2	Transformers	TR1 and TR2 TR3 and TR4	1000 MVA (230kv/500kv) 1000 MVA (18kv/230kv)
3	Load	L1, L2 and L3 Equivalent Load	200+200+100 MW 15000MVA/500KV
4	Bus Rating	Bus 02 and Bus 03 Bus 01, 04, 05, 06, 07, 08, 09	13.8KV 500KV
5	Transmission line	Inductance (L1-L6) Length (each)	4.12mH 25km
6	Sys; Nominal Frequency		60Hz

3.3 Three Phase Fault:

A three phase fault will be applied on the Bus 08 of bus of IEEE 9 bus system. The system will undergo severe transients and its performance will badly effect due three phase fault. After some delay the system will try to retain its original steady state condition. To reduce this delay and to enhance the performance of system by controlling the power flow and maintain the active power and voltage during fault condition, we will implement different FACTS devices one by one on the bus 05 of system and compare the performance system with and without the FACTS devices. Also the efficiencies of different FACTS devices will also be compared in affecting the performance of system.

3.4 Power System Evaluation with Three Phase Fault:

Power system performance will evaluate under fault condition by applying a three phase fault at bus 08. The transients produced will affect the performance of system badly and some of buses will go under and overloaded due to non-uniform distribution of power of among buses. To overcome such condition and to maintain the performance of system, FACTS devices will be implemented one by one on bus 05. After the implementation of FACTS device, the performance of system will get better and the transients will almost remove from the system [34].

3.5 The determination of location of FACTS controllers:

The FACTS controllers were placed on the location in such a way that the capability of FACTS controllers to compensate a particular bus or line could be optimized. Therefore, it is best if the FACTS controllers would be located shunt with the weakest bus (in the case of shunt connected FACTS controllers) or series with line that have the lowest percentage of underutilize capacity or higher power losses in the selected voltage magnitude profile (in the case of series connected FACTS controllers).

Therefore, continuous power flow analysis was applied in order to determine the weakest bus and the underutilized line in the test system. The test system was analyzed without the FACTS controllers and hence the original performance of the test system was required. Voltage magnitude profiles (bus voltage in per unit versus the increasing loading parameter) for all the buses in the test network were plotted and the bus in which collapses the worst among other buses has been selected as the weak bus. On the other hand, based on the power flow report, the most underutilized line or higher power losses in the selected voltage magnitude profile were determined. The line in which has the lowest power flow out of its total rating was selected as the line that needs series compensation [35].

3.5.1 The Performance of Series Connected FACTS Controllers

After the determination of FACTS controllers' location, the FACTS controllers were inserted in the tested network. The series FACTS controllers were placed in series with the selected line. There is one type of series connected FACTS controllers that would be used, which is SSSC. In order to evaluate the performance of each series connected FACTS controllers, the FACTS controllers would be placed one by one. By this way, we could compare the performance of each FACTS controller. A power flow would be used for the method in evaluating the performance of FACTS controllers. We would acquire the voltage profile for every bus and the power flow for each line.

3.5.2 The Performance of Shunt Connected FACTS Controllers

The shunt FACTS controllers would be placed in parallel with the selected bus. There is one type of shunt connected FACTS controllers that would be used, which is STATCOM. In order to evaluate the performance of each shunt connected FACTS controllers, the FACTS controllers would be placed separately. By this approach, we could compare the performance of each FACTS controller. A power flow would be used for the method in evaluating the performance of FACTS controllers. We would acquire the voltage profile for every bus and the power flow for each line.

3.5.3 The Performance of Shunt-Series Connected FACTS Controllers

Based on the lowest voltage magnitude, then following by underutilized line or higher power losses in the selected voltage magnitude profile determined earlier, we place the shunt-series on the line with series part of compensator connected in series with the line and shunt part of compensator shunted with the line. The compensator would be placed in the middle of the line, meaning that the line impedance would have to divide by two. For this combined compensator, we would only consider of using only one FACTS controller, which is the UPFC. The performance analyzing method is actually similar with the previous method used for series and shunt connected FACTS controllers. With this approach, voltage profile for every buses and the power flow for each line and hence we would obtain enough data to compare with.

3.6 Summarized Flow Chart

The methodology adopted above is best explained by means of a flow chart. Figure below shows the summarized the flow chart of the adopted methodology. Figure 3.3 the flow chart of methodology adopted.

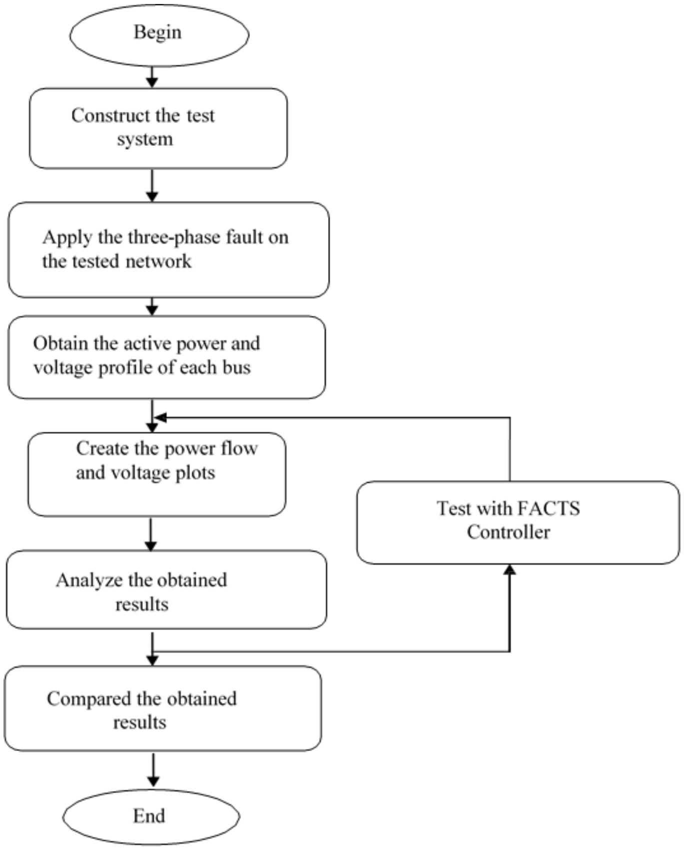

Figure 3.4: The flow chart of methodology adopted

The first thing is the selected test system, which the IEEE 9-bus test system was constructed by using the MATLAB/PSAT. The blocks that modeled the power system apparatus were used to create the test network. Then, the power flow was applied on the test system without the consideration of FACTS controllers (base case) to obtain the performance of the system without any compensator, and hence obtained the location for FACTS controllers' placement.

The implementation of power flow in the system yielding the voltage magnitude profile of each bus and also the power flow report that was used in the determination of location for FACTS controllers. Shunt controllers were placed at the bus in which has the worst voltage profile. While series FACTS controllers on the other hand, were placed in series with the line that have the highest percentage of underutilized capacity or higher power losses in the selected voltage magnitude profile. Note that the FACTS controllers were inserted one at a time to ensure performance of each FACTS controller could be observed and analyzed.

Simulation and Results

4.1 Introduction

The results obtained from the simulation done in MATLAB Sim Power System are presented here. These simulations and results are then followed by analysis and discussion which includes the load flow analysis and power system performance during fault condition.

The simulation was involving the 9-bus test system without the consideration of any FACTS controllers, meaning it was just to measure the system performance during fault condition by applying three-phase fault to the system, without the FACTS compensation effect. Then, the system performance was measured with STATCOM, SSSC and UPFC effects taken into account

4.2 Steady-State Condition

The proposed power system in figure 4.1 is analyzed during steady state condition when there is no fault injected to power system and the system operates normally without being disturbed.

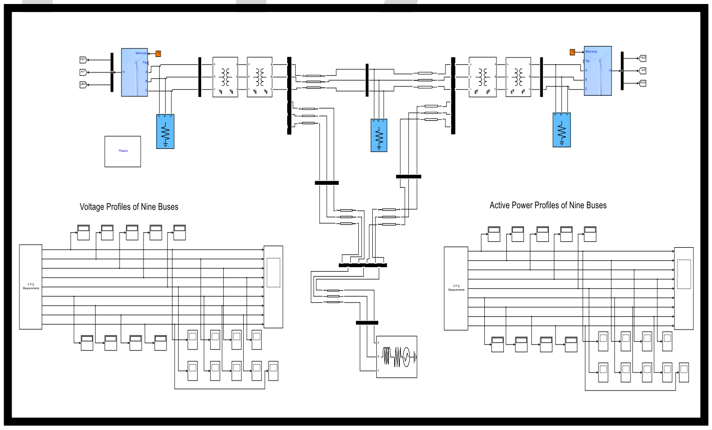

Figure 4.1: IEEE Nine Bus System during Steady-State Condition

During the steady state condition, it is observed that voltage and power flow through each bus are remain constant with having small transients which are the result from non-uniform power of generation plants. The active power flow and voltage profiles calculated during steady state condition are given below:

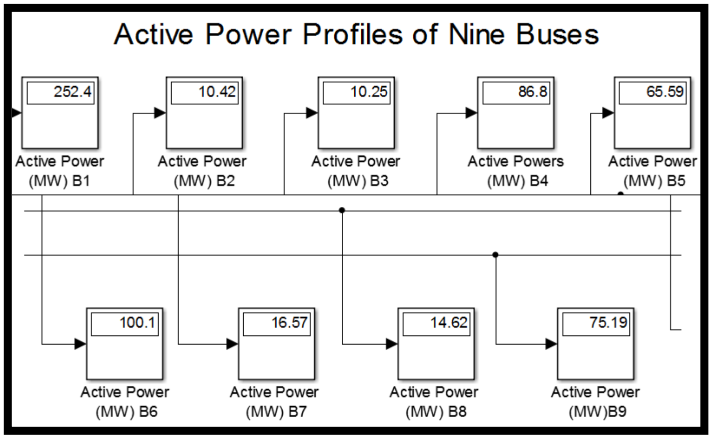

Figure 4.2: Active Power Flow Profiles during Steady State Condition

The active power flow and voltage profiles calculated during steady state condition of power system, are shown in figure 4.2 and 4.3 respectively. The active power through each bus flows at its maximum nominal values with small oscillations in it. The power flow through each bus remain uniform throughout the operation of power system. This is due to the fact that the generators remain in synchronization during steady state condition and deliver maximum active power to the power source connected to bus 01 without being disturbed. After the disturbance, this condition may not remain longer and generator will fallout of synchronism.

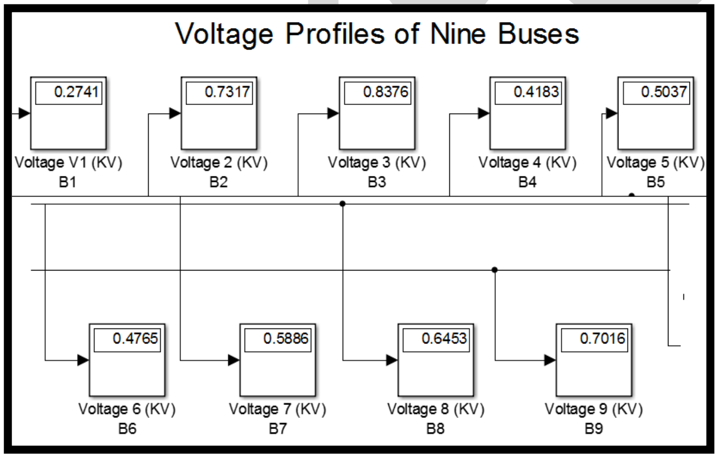

Figure 4.3 Voltage profiles during Steady State Condition

4.2.1 Active Power Flow profiles during Steady State Condition:

Three buses out of nine will be consider for analyzing through the research which are bus 01, bus 05 and bus 08. The reason is that fault will be created on bus 08 and FACTS device will be Injecting to bus 05 while bus 01 is connected to power source which is consuming the generation of two power plants. Figure 4.4, 4.5, 4.6 shows the plots of selected buses, respectively.

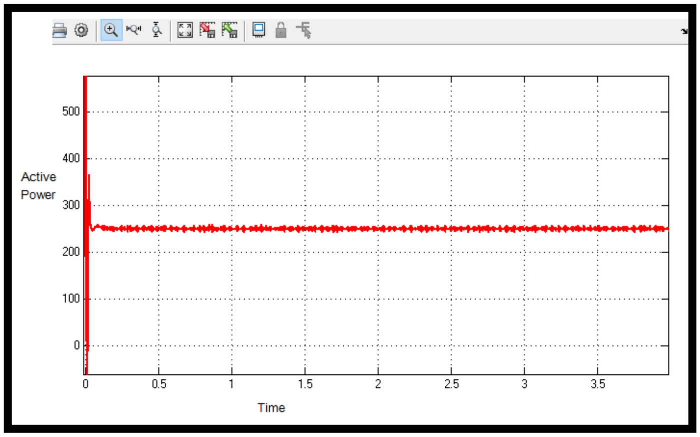

Figure 4.4: Bus 01 Active Power Flow Plot during Steady State Condition

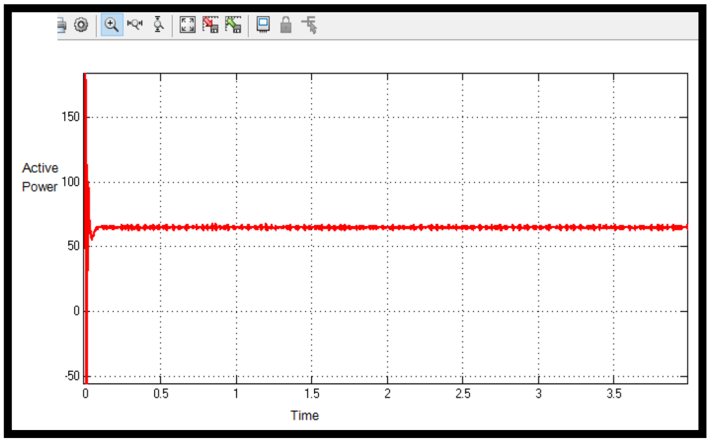

Figure 4.5: Bus 05 Active Power Flow Plot during Steady State Condition

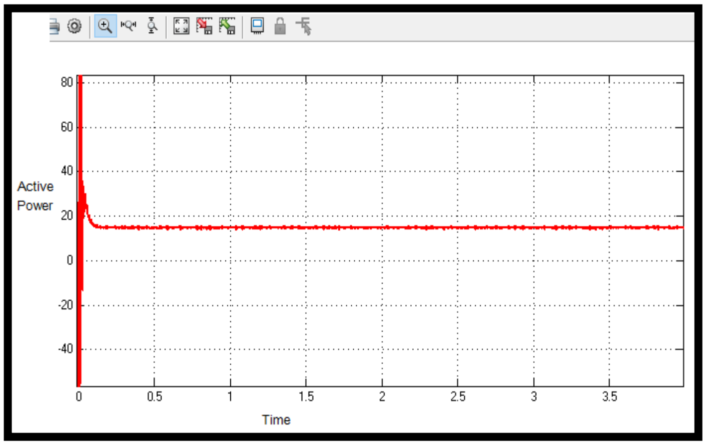

Figure 4.6: Bus 08 Active Power Flow Plot during Steady State Condition

4.2.2 Voltage Profiles during Steady State Condition:

The voltage profiles of bus 01, bus 05 and bus08 have been analyzed during steady condition through plots constructed in MATLAB, shown in figure 4.7, 4.8 and 4.9 respectively. As there is no such disturbance occurred during steady state condition, the voltage across each bus is remain uniform through the operation of power system. Though there are small transients can be seen in voltage plots, which are the result of generators output power.

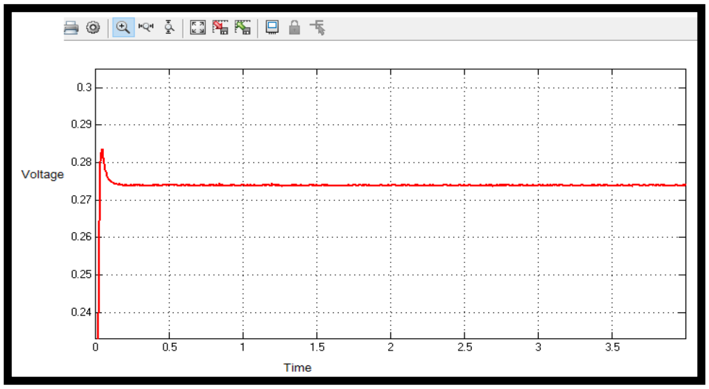

Figure 4.7: Bus 01 Voltage Plot during Steady State Condition

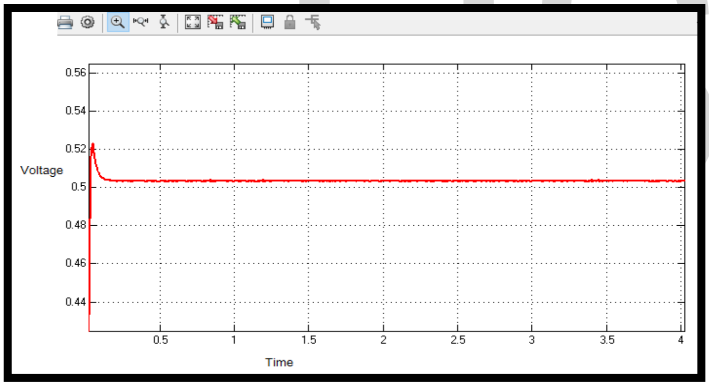

Figure 4.8: Bus 05 Voltage Plot during Steady State Condition

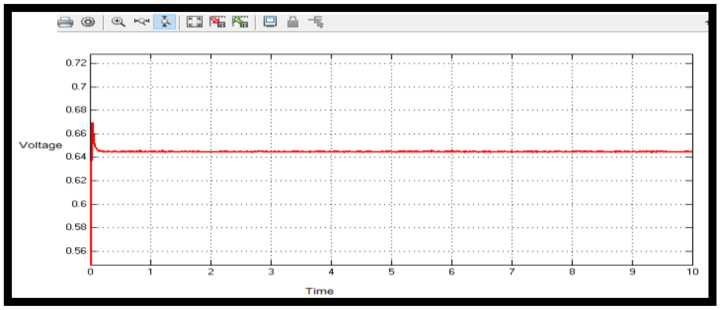

Figure 4.9: Bus 08 Voltage Plot during Steady State Condition

4.3 Evaluation of IEEE 9-bus system performance during fault Without FACTS Controllers:

For the Base Case, the simulation is not inclusive of any FACTS controllers, but only inclusive

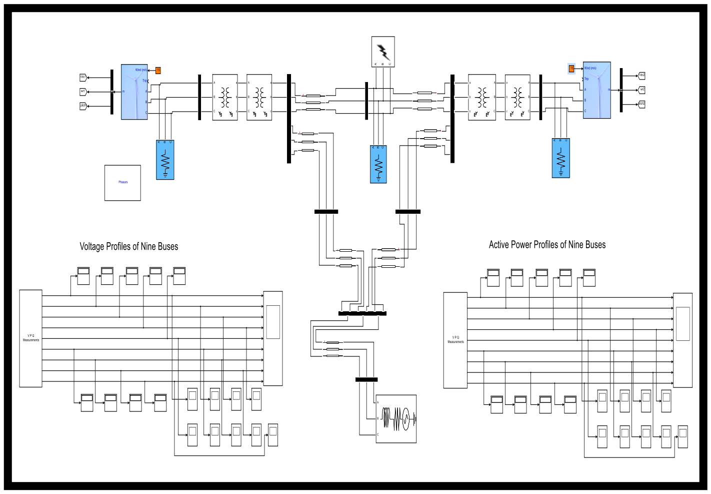

Figure 4.10: IEEE 9-Bus System including 3-phase fault without FACTS Controllers

With two wind generators and an equivalent load. Three-phase fault is applied to bus 08, to measure the performance of the system without the consideration of any FACTS controllers. The IEEE 9-bus test system that was simulated and shows as above in figure 4.10.

The IEEE 9-bus system consists of 9 buses and 4 loads. The total generation and load of the system is 2000MW and 15500MVA respectively. After the simulation is being ran for 10 seconds, the voltage and active power profiles of each bus are been plotted, with the help of which we will evaluate the performance of system during three phase fault condition, applied to bus 08, without using any FACT controller. The voltage and active power profiles resultant from simulation for 10 seconds are shown in figure 4.11 and figure 4.12. From these profiles the weakest buses and overloaded buses will be determined with the help of VPQ measurement blocks.

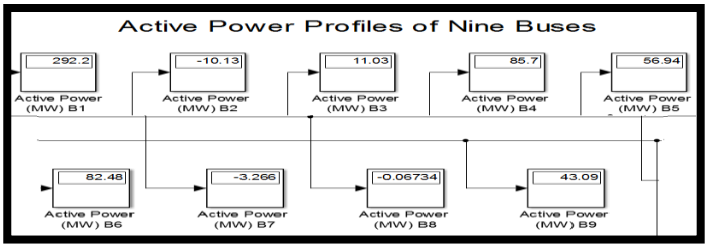

Figure 4.11: Active Power Profiles of nine buses during fault

From above figure 4.11 active power profiles can be easily evaluated. Due to three phase fault applied on bus 08, the bus 08 is occurred to be weakest bus as its active power flow is decrease down to -0.06734MW. Other weak buses are Bus 02, bus 05, bus 07 with active power flow of -10.12MW, 56.94MW and -3.266MW respectively.

Figure 4.12 represents the voltage profiles of each bus. Three phase fault has badly effect the voltage profiles across every bus. The voltage of bus 08 is goes down to 2.041e-05MW and it is determined to be weakest bus. Other buses effected from fault are bus01, bus04, bus05 and bus06 with voltage profile of 0.009871MW, 0.0148MW, 0.0251MW and 0.0352MW respectively.

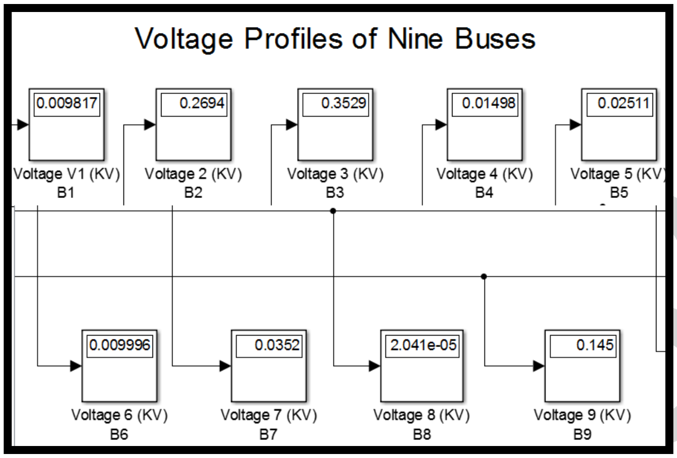

Figure 4.12: Voltage Profiles of nine buses during fault

4.3.1 Analysis of fault effected buses with plots:

The buses which are affected from fault will be evaluated by constructing a plots for each bus in MATLAB. From plots the performance and capability of each and every effected bus can be determined clearly. The plot for each bus is construct for duration of 10 seconds which is enough to evaluate the transients produced at bus due to three phase fault.

4.3.2 Analysis of Active Power Flow of fault effected buses:

Figure 4.13 shows the plot of bus 01 during fault. It can be clearly observed that the oscillations produced due to fault are very high and need to be damped. These high oscillations lead to the generation of transients in system due to which system's performance can severely effect. The bus 01 is found to be overloaded.

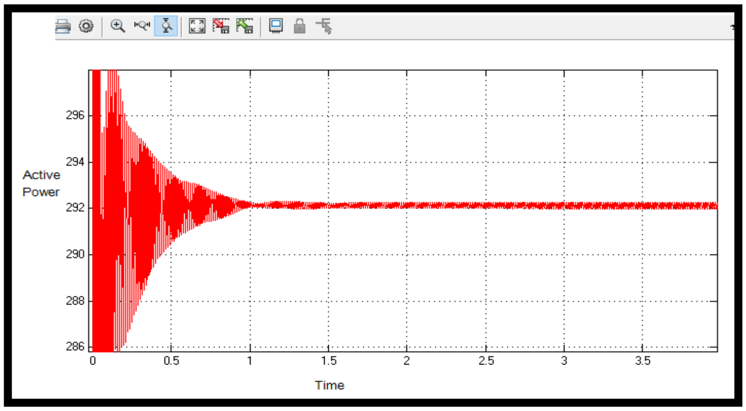

Figure 4.13: Bus01 Active Power Flow Plot during Fault without FACTS

Figure 4.14 shows the oscillations occurred in bus 05 due to fault. Although the level of power flow through bus 05 is very much considerable but the oscillations produced due to fault are continuous and need to be damped before they effect on power system.

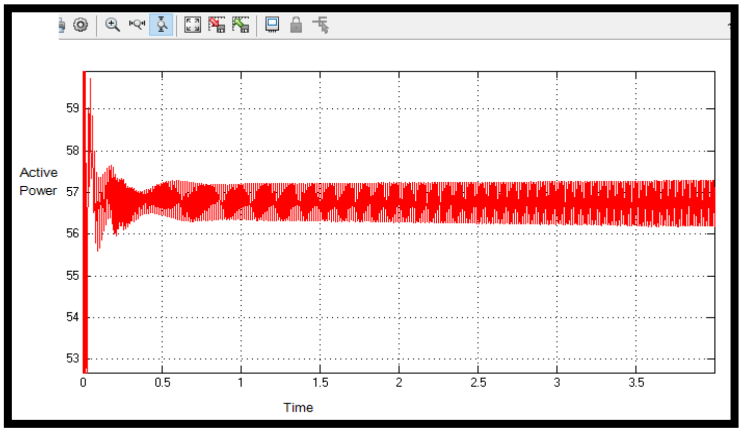

Figure 4.14: Bus05 Active Power Flow Plot during Fault without FACTS

As the fault is applied at bus 08, its power flow level goes down to almost zero and it becomes under-loaded. The oscillations produced on bus 08 for very short duration of time, are extremely high and leave the bus with almost non-operational condition. Figure 4.15 shows the power flow profile of bus 08. The power flow of bus 08 also flows in opposite direction after the occurrence of disturbance.

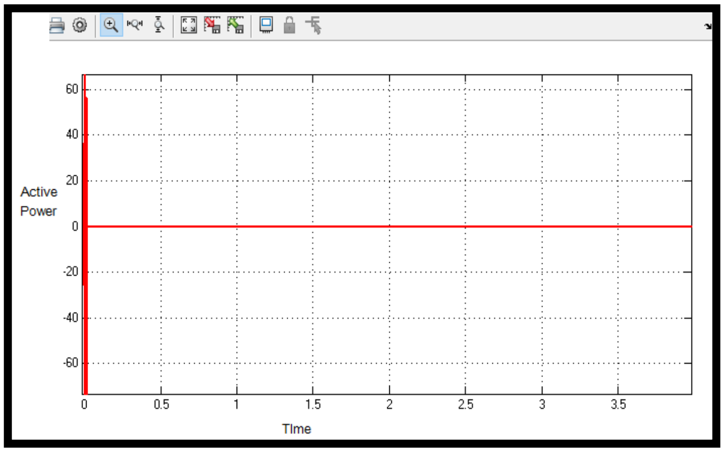

Figure 4.15: Bus08 Active Power Flow Plot during Fault without FACTS

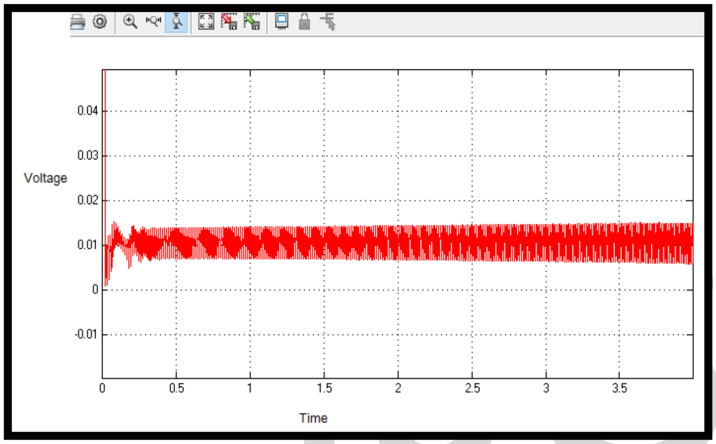

Figure 4.16: Bus01 Voltage Plot during Fault without FACTS

4.3.3 Analysis of voltage profiles of fault affected buses

With the disturbance of flow of active power throughout the system, voltage profiles are also being affected due to three phase fault. Figure 4.16 shows the result of bus 01 situation during fault condition. Its voltage is decrease down to almost zero. The transients and oscillation can be clearly observed. This disturbance occurred when three phase fault is applied to bus 08 due to which the generators fallout of synchronization and operation of running power system is badly affected. The fallout of generators from synchronization makes the power system unstable for the moment and very large transients and oscillations are produced on each bus as power generation from each generator don’t match with each other as both are out of phase and need to be bring to its original operating position.

The voltage profile of bus 05 is shown in figure 4.17. The voltage of bus 05 bus is dropped to a very low level due to fault occurrence in system. In spite of voltage drop in bus, high transients and oscillations also generates on the bus which lead the power system to instability.

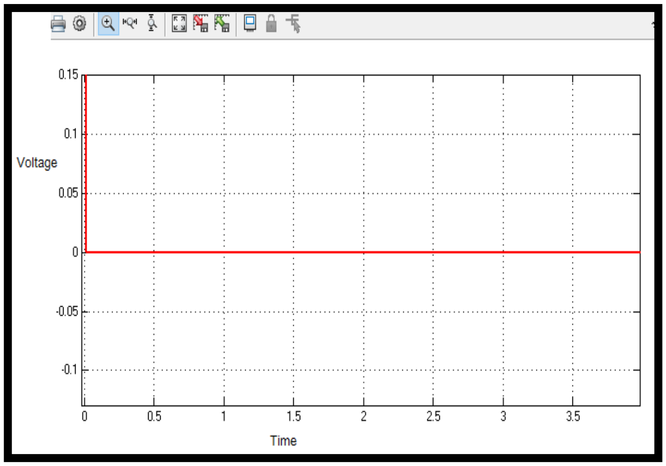

Figure 4.17: Bus05 Voltage Plot during Fault without FACTS

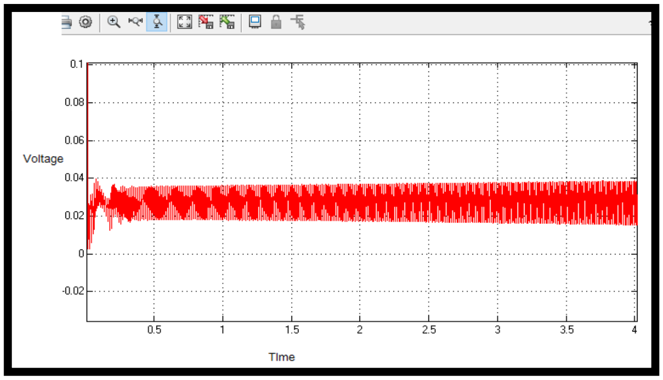

Figure 4.18: Bus08 Voltage Plot during Fault without FACTS

The three phase fault is applied on bus 08, its voltage is dropped abruptly to a very small value of MW which can be seen as a straight red line in figure 4.18. This bus is severely collapsed due to fault and required to return to its original condition otherwise the system will remain unstable for a long duration and its equipment can be damaged.

From above discussion and analysis of various buses which are much effected from three phase fault, through different plots, it is then required to improve the performance of those buses in order to avoid the system lead to instability. So to make the system’s operation continuous and stable during fault, FACTS controllers will be implemented in IEEE 9 bus system to improve the performance and reliability of system. For testing and analysis of FACTS devices, bus 05 is considered where one of FACT controller will be implemented. Three testing methods will be used to analyze the result of power system with FACTS controllers during occurrence of fault at bus 08.

The three testing methods are discussed below:

i. Simulation and Evaluation of IEEE 9-bus system performance during fault with STATCOM.
ii. Simulation and Evaluation of IEEE 9-bus system performance during fault with SSSC
iii. Simulation and Evaluation of IEEE 9-bus system performance during fault with UPFC.

4.4 Evaluation of IEEE 9-bus system performance during fault with STATCOM:

STATCOM is being connected in parallel to bus 05 of power system as shown in figure 4.19. As STATCOM is voltage regulator, its reference voltage Vref is set to 1.00 p.u, so it will inject 10% of total sys tem voltage to regulate the voltage profiles of all buses. The convertor rating of STATCOM is kept at 100MW as compared to buses rating. The DC link of convertor is set at 350e-6 farad, as it stores the power for STATCOM operation.

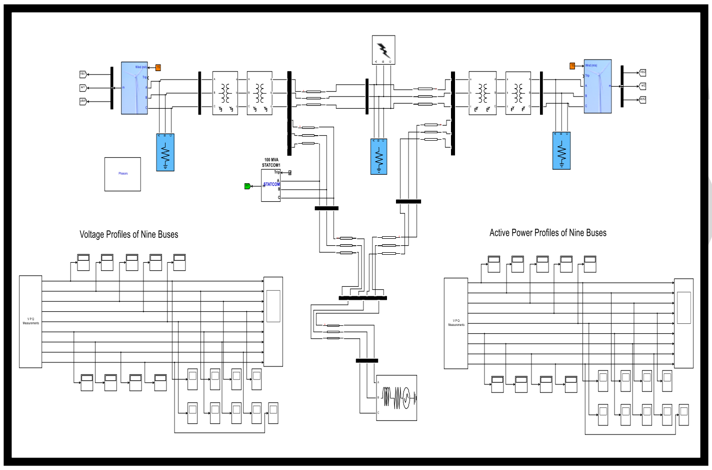

Figure 4.19: IEEE 9-Bus System including 3-phase fault with STATCOM

4.4.1 Analysis of Buses voltage profiles during fault in the presence of STATCOM:

The voltage across each bus is shown in figure 4.20, by means of digital meters. It is clearly observed that the voltage profile of each bus is significantly improved after the implementation of STATCOM at bus 05 of power system. STATCOM has supplied 1.0 p.u of voltage during fault to enhance the voltage of buses which would avoid the system to face instability while undergoes through disturbance.. The plots and waveforms of buses voltages are further discussed below.

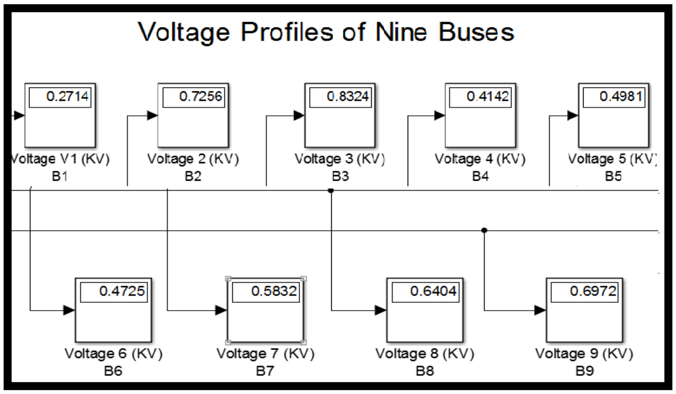

Figure 4.20: Voltage Profiles of nine buses with STATCOM

The waveforms of bus 01 are shown in figure 4.21. The voltage of bus 01 is step up to 0.2714MW from 0.009817MW after the insertion of STATCOM into system. As shown in sub-graph, there are still oscillations and transients left in a bus as STATCOM is not much efficient to make the signal smooth and uniform.

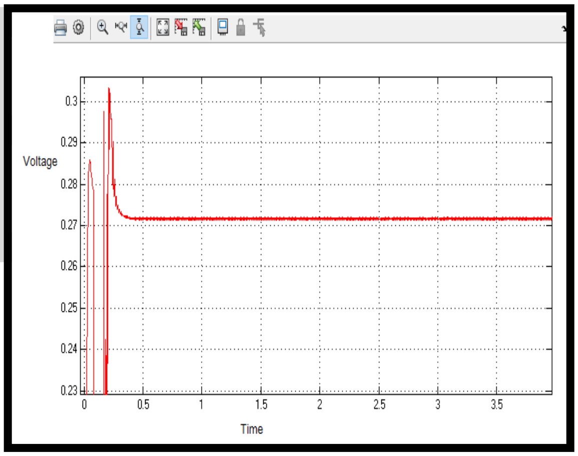

Figure 4.21: Bus01 Voltage Plot during Fault with STATCOM

As STATCOM is injected to bus 05 of power system, the voltage of bus 05 is increased to 0.4981MW from 0.02511MW by injecting a voltage of 1.0 p.u to the system. The magnitude of voltage of bus 05 is significantly increased which also effects on performance of overall system but on the other hand the small oscillations and transients are still left in the bus voltage, shown in figure 4.22, which may not good for system operation.

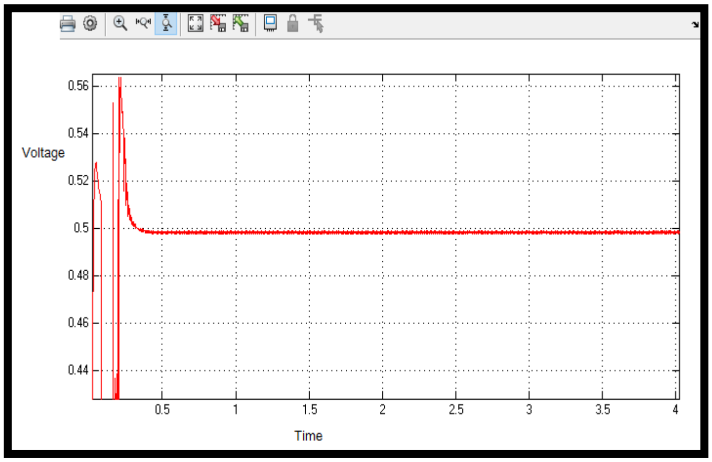

Figure 4.22: Bus05 Voltage Plot during fault with STATCOM

Three-phase fault is applied on bus 08 due to which its voltage is dropped down to a very low magnitude and effects its operation badly. After the insertion of STATCOM into the system during fault, the voltage across bus 08 is enhanced to 0.6404MW from 2.04e-05MW which shows that STATCOM has significantly improved the voltage profile of bus 08. Transients of low frequencies are still remains in bus 08 as in other buses of system. Plot of bus 08 voltage is shown in figure 4.23.

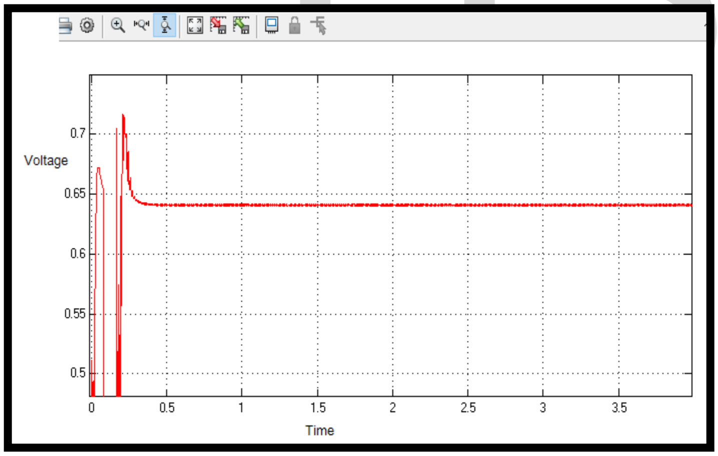

Figure 4.23: Bus08 Voltage Plot during Fault with STATCOM

The voltage waveforms of all nine buses of power system are shown in figure 4.24. The voltage magnitude profiles of all nine buses are improved significantly during disturbance when the STATCOM is introduced to the proposed system. Although STATCOM has lacking the ability of removing transients and damps completely, as there are small oscillations has left in the system. The following improvement differences are shown in Table 4.1:

Table 4.1: Voltage Profiles Differences of nine buses using STATCOM

Bus No	Bus Voltage without STATCOM during fault	Bus Voltage with STTACOM during fault
1	0.009871KV	0.2714KV
2	0.2694KV	0.7256KV
3	0.3529KV	0.8324KV
4	0.01498KV	0.4142KV
5	0.02511KV	0.4981KV
6	0.009996KV	0.4725KV
7	0.0352KV	0.5832KV
8	2.041e-05KV	0.6404KV
9	0.145KV	0.6972KV

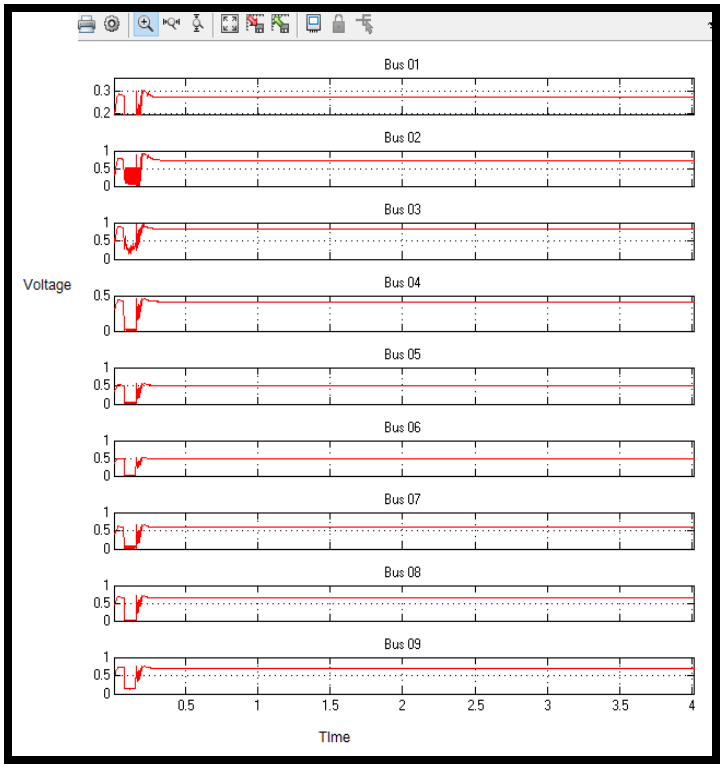

Figure 4.24: Voltage Plots of all nine buses during fault with STATCOM

4.5: Evaluation of IEEE 9-bus system performance during fault with SSSC:

SSSC is being connected in series to bus 05 of power system as shown in figure 4.25. As SSSC is efficient at regulating power flow by reducing the high oscillations and transients in system, which are produced to due to three phase fault applied at bus 08. The convertor rating SSSC is kept at 100MW as compared to buses rating. The DC link of convertor is set at 350e-6 farad, as it stores the power for ssc.

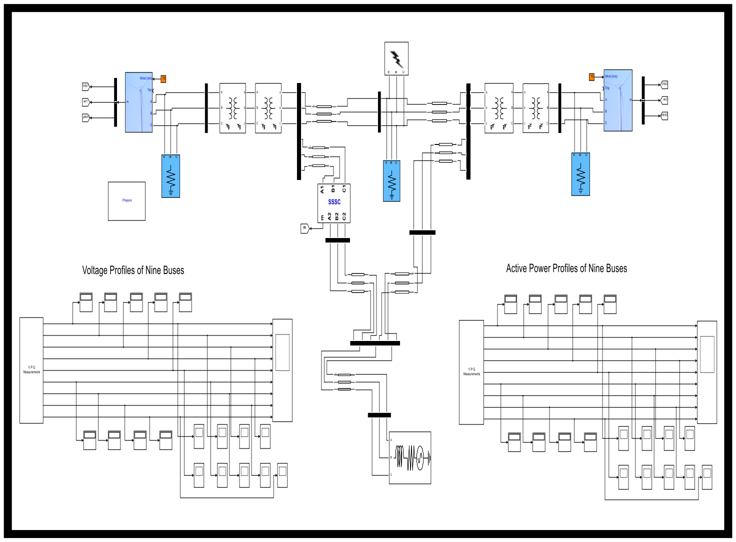

Figure 4.25: IEEE 9-Bus System including 3-phase fault with SSSC

4.5.1 Analysis of Buses Active Power Flow Profiles during fault in the presence of SSSC:

The active power flow in each bus is shown in figure 4.26, via digital meters. It is clearly observed that the active power flow profile of each bus is significantly improved after the implementation of SSSC at bus 05 of power system. SSSC has supplied enough amount of active power during fault to enhance the power flow of entire system which would avoid the system to face instability while facing disturbance. The plots and waveforms of buses active power flows obtained during current condition are discussed below further.

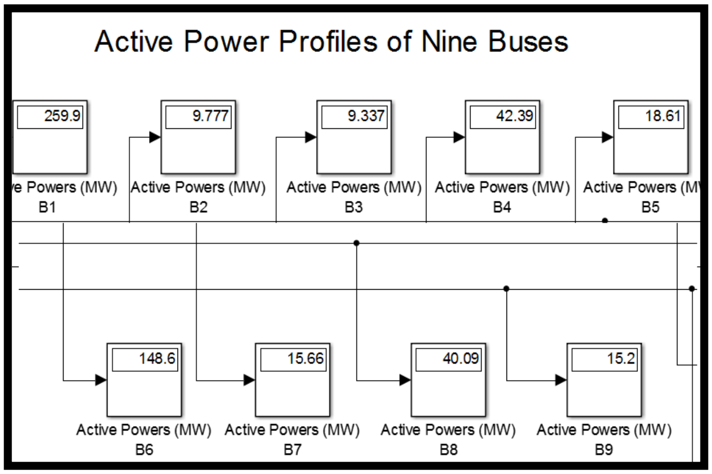

Figure 4.26: Active Power Flow measurements of nine buses with SSSC

The active power flow of bus 01 is shown in figure 4.27. SSSC has significantly controlled the active power at all buses and bring the active power flow level at every bus to a considerable level

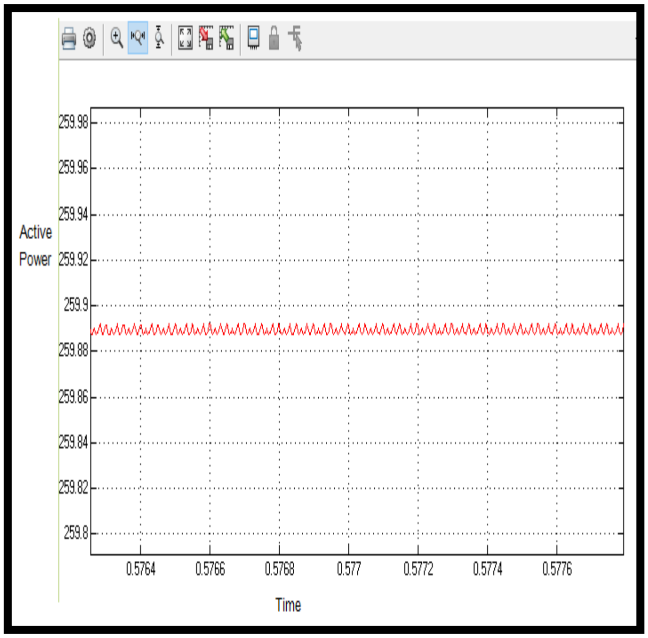

Figure 4.27: Bus01 Active Power Plot during Fault with SSSC

Of flow. The power flow at bus 01 is 259.9MW (with SSSC) which is reduced from 292MW (without SSSC), this shows that SSSC has relief the bus 01 from over flow of power during fault and more important the transients and oscillations are minimized to a very small level.

The SSSC is injected to bus 05. The power flow of bus 05 is also decresead to 18.61MW from 55MW, shown in figure 4.28, which is may more reduction of power than its considerable level but more importantly oscillations have been reduced to a very large extent which is a good sign for system reliable operation.

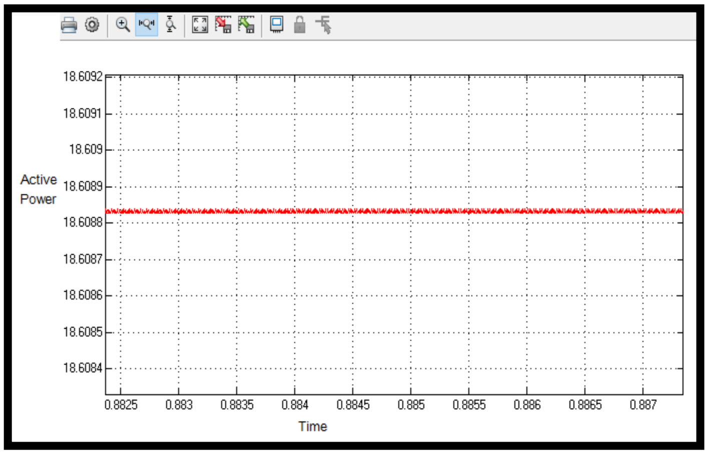

Figure 4.28: Bus05 Active Power Plot during Fault with SSSC

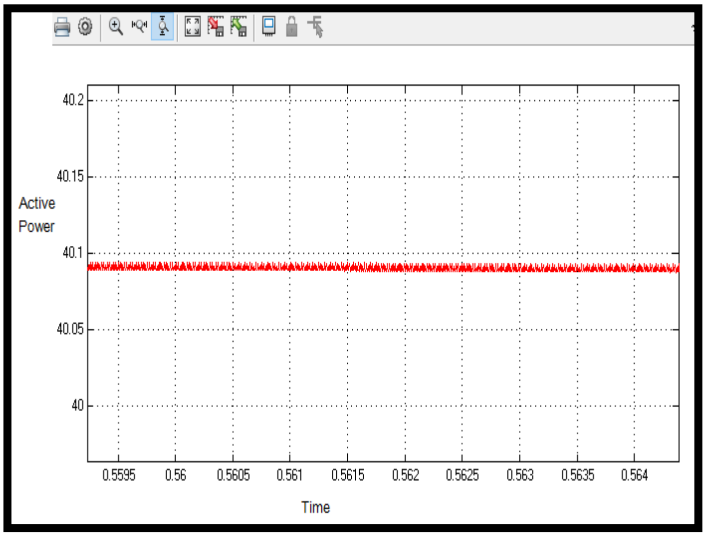

Figure 4.29: Bus08 Active Power Plot during Fault with SSSC

As three-phase fault is applied to bus 08, its active power flow capability is badly disturbed and its power turned to flow in negative direction which can badly effect the system operation. The active power flow of bus 08 is improved as well as transients and oscillations are also minimized after the insertion of SSSC to the system. Bus 08 active power flow increased to 40.09MW from -0.06734MW , shown above in figure 4.29.

The active power flow waveforms of all nine buses of power system are shown in figure 4.30. The active power flow profiles of all nine buses are improved significantly during disturbance when the SSSC is introduced to the proposed system. Although SSSC has doesn't improved the magnitude of active power at all buses efficiently but the transient and damps are excellently improved by it. The following differences of active power flow magnitudes before and after the insertion of SSSC are shown in Table 4.2:

Table 4.2: Active Power Flow Profiles Differences of nine buses using SSSC

Bus No	Bus Active power flow without SSSC during fault	Bus Active power flow with SSSC during fault
1	292.2 MW	259.9 MW
2	-10.1 3MW	9.777 MW
3	11.03 MW	9.337 MW
4	85.7 MW	42.39 MW
5	56.94 MW	18.61 MW
6	82.48 MW	148.6 MW
7	-3.266 MW	15.66 MW
8	-0.06734 MW	40.09 MW
9	43.09 MW	15.2 MW

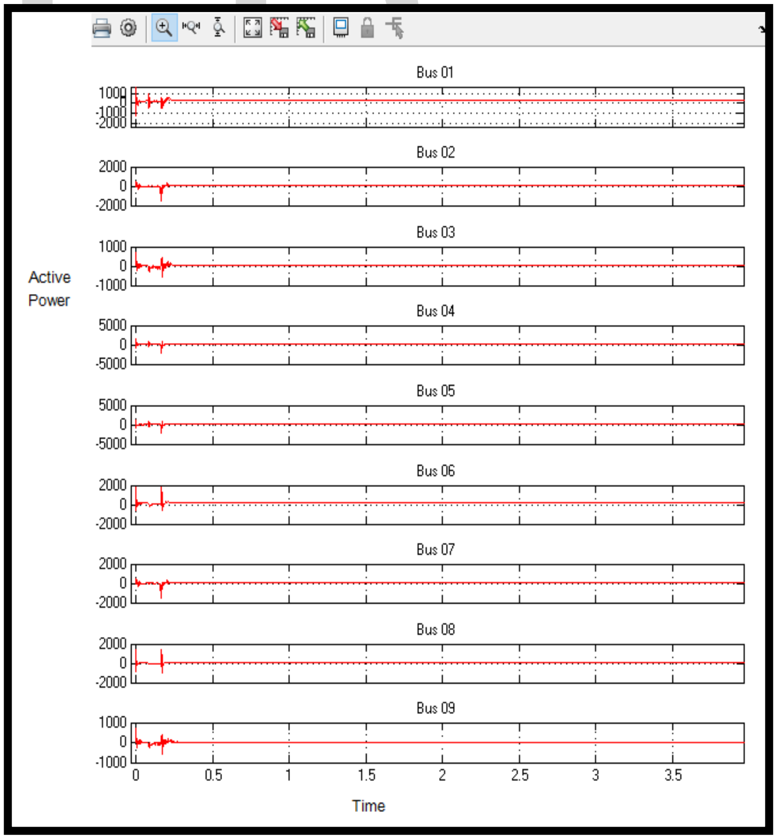

Figure 4.30: Active Power Flow Plots of all nine buses during fault with SSSC

4.6 Evaluation of IEEE 9-bus system performance during fault with UPFC:

In the final phase of research, UPFC is connected to bus 05 of power system, shown in figure 4.31. As UPFC consists of both SSSC and STATCOM convertors, so it has the capability to improve both active power and voltage profiles simultaneously as well as can eliminate the damps and transients from the system completely. The ratings of both convertors are kept at 100MW as compared to system rating. While the capacitance rating is kept at 750e-06, which is used to supply power to UPFC while its operation. The performance of UPFC is evaluated in detail in below plots of active power flow and voltage.

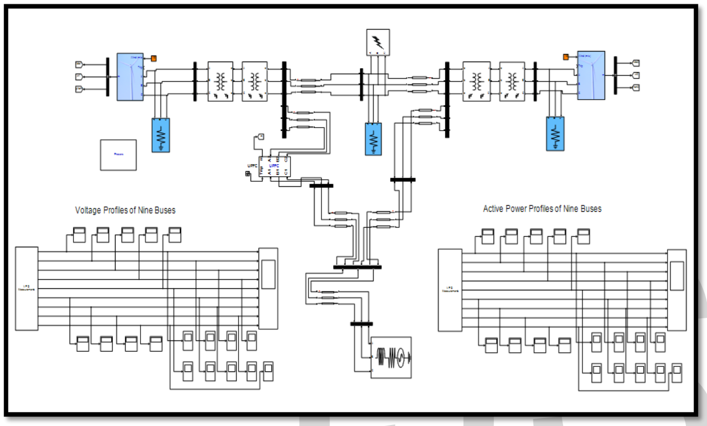

Figure 4.31: IEEE 9-Bus System including 3-phase fault with UPFC

4.6.1 Analysis of Buses Active Power Flow Profiles during fault in the presence of UPFC:

The active power flow profiles in presence of UPFC is shown in figure 4.32, via digital meters. UPFC has significantly improved the active power flow on all nine buses as well as completely eliminated and damped the oscillations and transients from all the buses which make the system very stable to operate during fault condition. The main advantage of UPFC is that it has completely eliminate the transients from system which is focus of research to make the system's operation fully stable and uniform. The plots and waveforms of chosen buses constructed under UPFC are discussed below.

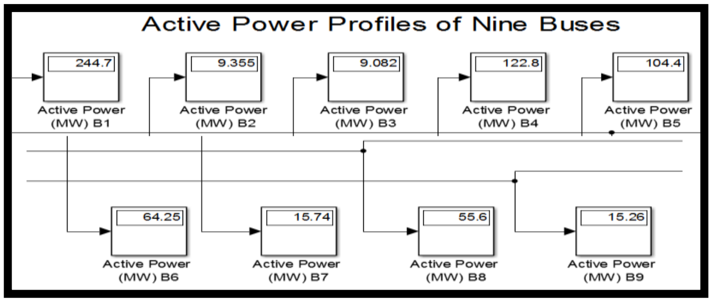

Figure 4.32: Active Power Flow measurements of nine buses with UPFC

The active power flow of bus 01 is shown in figure 4.33. UPFC has significantly controlled the active power at all buses and bring the active power flow level at every bus to a considerable level of flow. The power flow at bus 01 is 244.7 MW (with UPFC) which is reduced from 292MW (without UPFC), this shows that UPFC has relief the bus 01 from over flow of power during fault and more important the transients and oscillations are completely vanished from the bus.

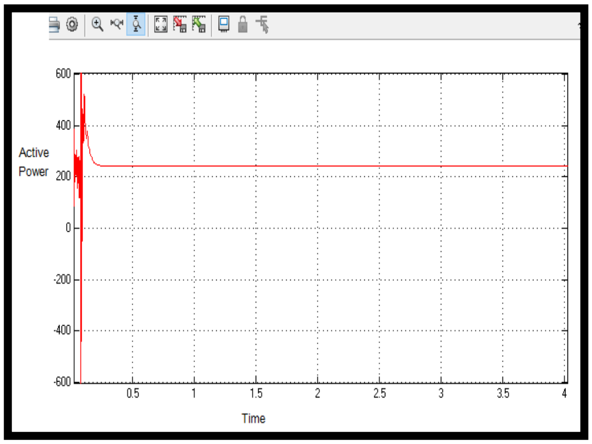

Figure 4.33: Bus01 Active Power Plot during Fault with UPFC

The UPFC is injected to bus 05. The power flow of bus 05 is also increased to 104.4MW from 55MW, shown in figure 4.34, which is the significant inrease in power flow improvemet at bus 05 and more importantly oscillations have been eliminated and vanished from the bus which could be dangerous for system operation.

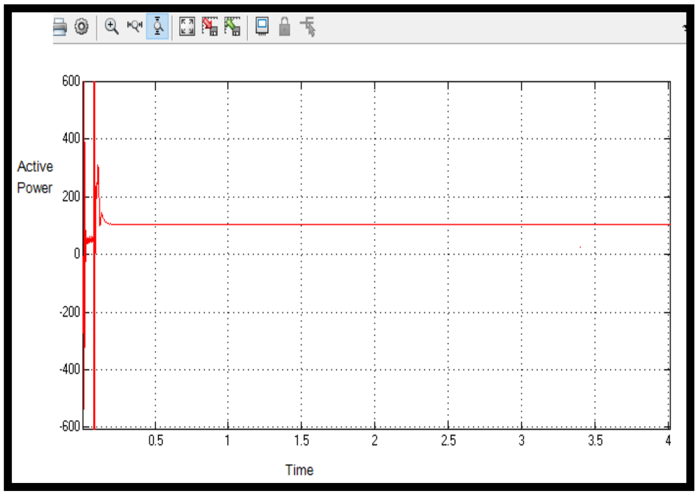

Figure 4.34: Bus05 Active Power Plot during Fault with UPFC

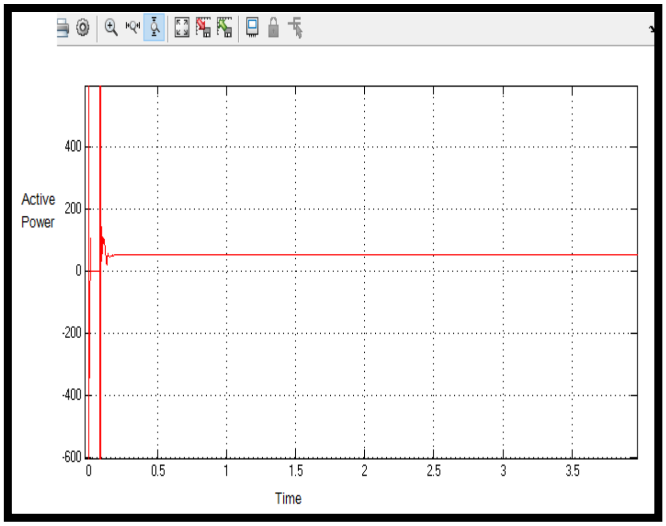

Figure 4.35: Bus08 Active Power Plot during Fault with UPFC

The performance of fault affected bus 08 is shown above in figure 4.35, under operation of UPFC. As fault has badly affected the bus active power flow and generates a very high transients and oscillations over the bus. UPFC has significantly performed its operation and not only improved the active power but also damps the oscillations and transients completely.

The active power flow waveforms of all nine buses of power system under operation of UPFC are shown in figure 4.36. The active power flow profiles of all nine buses are improved significantly during disturbance when the UPFC is introduced to the proposed system. UPFC has improved the both magnitude and transients very efficiently. The following differences of active power flow magnitudes before and after the insertion of UPFC are shown in Table 4.3:

Table 4.3: Active Power Flow Profiles Differences of nine buses using UPFC

Bus No	Bus Active power flow without UPFC during fault	Bus Active power flow with UPFC during fault
1	292.2 MW	244.7 MW
2	-10.1 3MW	9.335 MW
3	11.03 MW	9.028 MW
4	85.7 MW	122.8 MW
5	56.94 MW	104.4 MW
6	82.48 MW	64.25 MW
7	-3.266 MW	15.74 MW
8	-0.06734 MW	55.6 MW
9	43.09 MW	15.26 MW

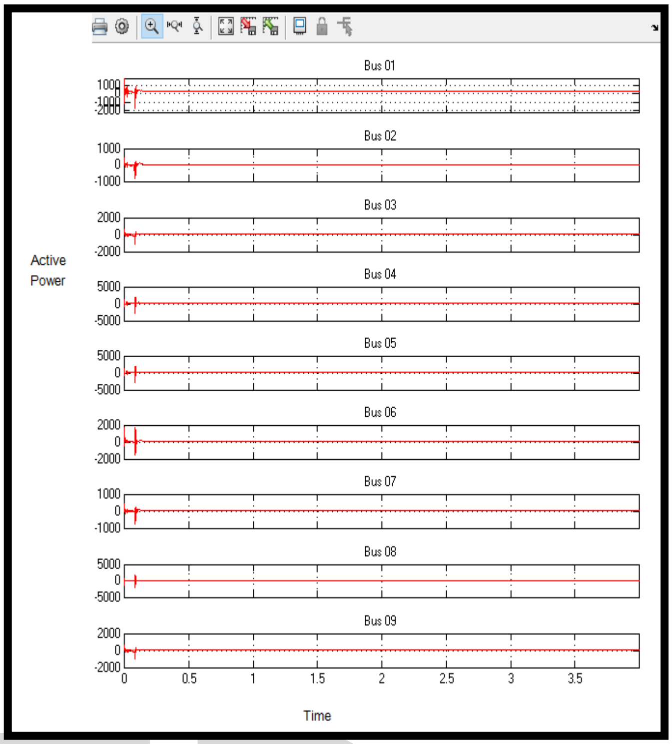

Figure 4.36: Active Power Flow Plots of all nine buses during fault with UPFC

4.6.2 Analysis of Buses Voltage Profiles during fault in the presence of UPFC

Magnitudes of voltage profiles improved by UPFC of nine bus system are shown in figure 4.37. The UPFC performance varies from STATCOM in some aspects, as there some buses whose magnitude is improved by STATCOM than UPFC but instead of only improvement of magnitude, STATCOM didn’t completely removed the transients and oscillations as UPFC did. So overall performance of UPFC is better than STATCOM. The plots and waveforms of chosen are discussed further below.

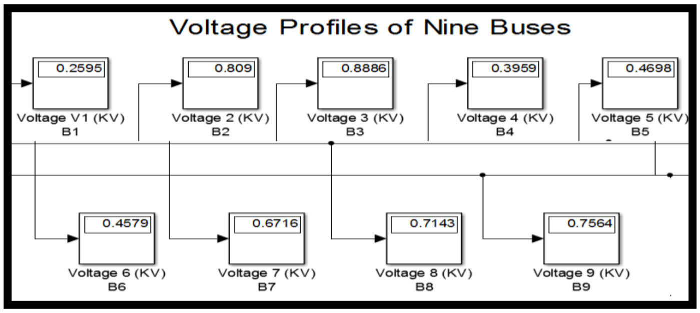

Figure 4.37: Voltage Magnitude Profiles of nine buses with UPFC

Performance of bus 01 using UPFC is shown through plot in figure 4.38. It is clearly observed that the voltage magnitude profile of bus 01 is improved from 0.009871MW to 0.2595MW. The UPFC has completely damp the oscillations as well, unlike STATCOM which didn't completely.

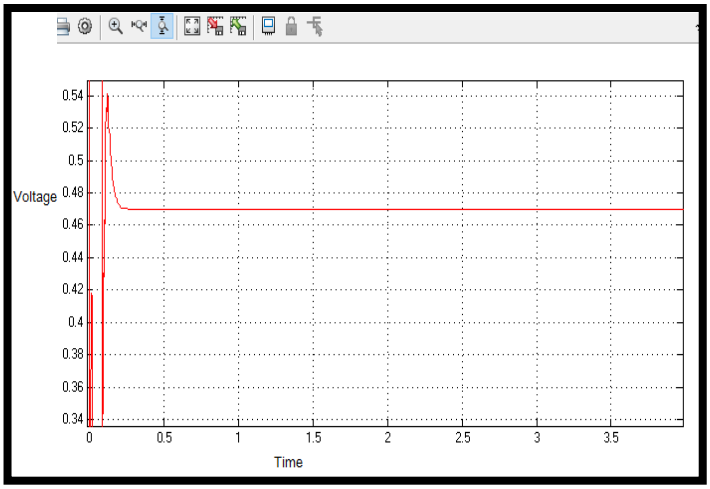

Figure 4.38: Bus01 Voltage Plot during fault with UPFC

The voltage plot of bus 05 is shown in figure 4.39. The transients and oscillations has been removed and voltage magnitude is improved to 0.4698MW from 0.02511MW by using UPFC.

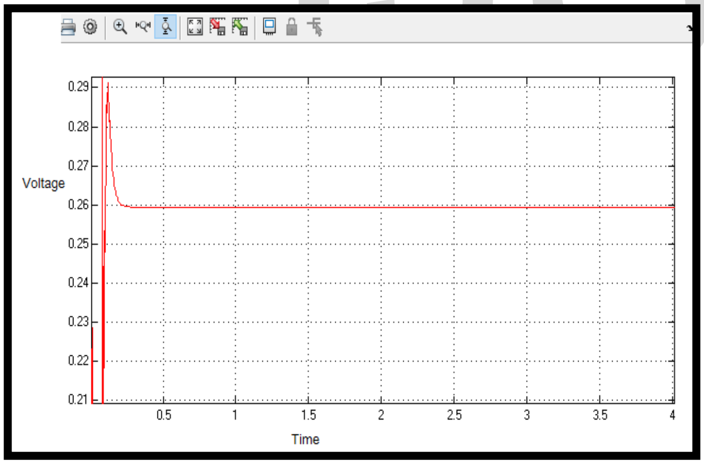

Figure 4.39: Bus05 Voltage Plot during fault with UPFC

As three-fault occurred on bus 08, its behavior gone almost abnormal due to generation of very high transients and damps as well as the voltage profile of the bus was badly affected. After the injection of UPFC to power system, its voltage improved to 0.7143MW from 2.041e-05MW and oscillations are completely removed, shown in figure 4.40.

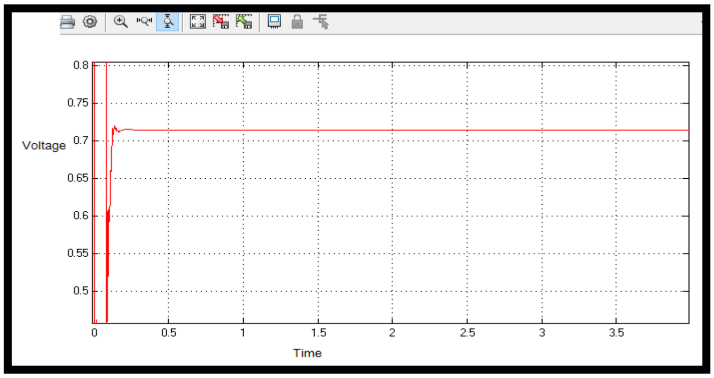

Figure 4.40: Bus08 Voltage Plot during fault with UPFC

The voltage waveforms of all nine buses of power system using UPFC are shown in figure 4.41. The voltage magnitude profiles of nine buses are improved significantly when the UPFC is introduced to the proposed system during disturbance. The transients and oscillations are completely damped from the system by using UPFC and made the operation of system stable and reliable. The following voltage magnitude profiles differences are shown in Table 4.4:

Table 4.4: Voltage Profiles Differences of nine buses using UPFC

Bus No	Bus Voltage without STATCOM during fault	Bus Voltage with STTACOM during fault
1	0.009871 KV	0.2595 KV
2	0.2694 KV	0.809 KV
3	0.3529 KV	0.8886 KV
4	0.01498 KV	0.3959 KV
5	0.02511 KV	0.4698 KV
6	0.009996 KV	0.4579 KV
7	0.0352 KV	0.6716 KV
8	2.041e-05 KV	0.7143 KV
9	0.145 KV	0.7546 KV

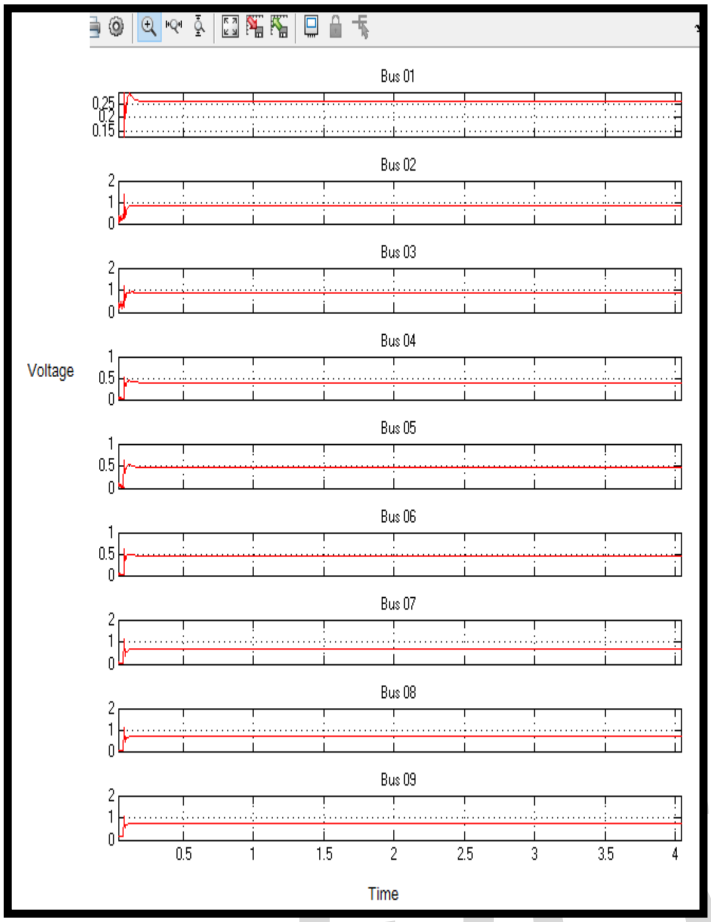

Figure 4.41: Voltage magnitude Plots of all nine buses during fault with UPFC

Conclusion

5.1 Research Conclusion:

The purpose of this project is to identify the effect of FACTS controllers in term of transient stability enhancement and power quality improvement when implemented it in power system. Three methods are used and several simulations have been run in MATLAB Sim Power System to test the IEEE 9-bus system with and without FACTS controllers. The performance of each FACTS controllers used have been evaluated. Therefore, it could be concluded that specific type of FACTS controllers would improves some of the power system parameters as well as helps in enhancement of transient stability. The FACTS controllers are tested one by one and found that each of FACTS controllers gives different amount of losses and power quality improvement. This project has successfully tested at the IEEE 9-bus test system and optimal condition of STATCOM, SSSC and UPFC also had been determined by analysis of the voltage magnitude profiles, active power flow and oscillation produced. The performance of the power system with different types of the FACTS devices also had been analyzed and found that UPFC give better effect to the performance of the system than STATCOM and SSSC as both of them were failed to remove the transients completely from the system. As a conclusion, the power flow, voltage and transient stability can be improved at fault condition by employing FACTS controllers.

5.2 Achievements of Research

This research has been carried out successfully. It has been proved from the analysis of different plots that UPFC have performed better than the STATCOM and SSSC. When if UPFC is placed in power system with low voltage magnitude and disturbed power flow during disturbance, it will give better results in the improvement of power quality and reduced power loss which is possible due to transients and oscillations produced due to fault occurrence. But when STATCOM and SSSC are placed in the power system with low voltage magnitude and disturbed power flow the results were not as effective as obtained during the placement of UPFC. Moreover, UPFC is a combination of STATCOM and SSSC, so that why it is much more effective than STATCOM and SSSC because UPFC can only not only improve the power quality but also eliminated the transients and oscillations completely from the system, which minimizes the power losses, can occurred due to these transients and oscillations.

5.3 Recommendation

This research work has proved that UPFC performed better than STATCOM and SSSC in injection of FACTS controllers to the IEEE 9-bus test system. There are a few recommendations for future work for improvement of this research work. The recommendations are listed as below:

i. Test the system using others FACTS controllers such as SVC and TCSC because different device can show different effect for transient stability improvement.

ii. Test the system using other simulation software like PSCAD, POWERWORLD, and other software because different software using different coding and different method.

iii. Test the FACTS controllers on a very large network, to view its capability handling complex network and overcoming transients in it.

iv. Find and develop new method to improve power system delivery quality for reduce losses and improve transient stability, voltage stability and other parameters of power system.

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