International Journal of Electrical, Electronics and Computer Engineering **2**(2): 117-126(2013)

ISSN No. (Online): 2277-2626

Voltage Level Improvement of Power System by the Use of STATCOM & UPFC with PSS Controller

Prity Bisen and Amit Shrivastava

Department of Electrical & Electronics Engineering,
Oriental College of Technology, Bhopal, (MP)

(Received 05 August, 2013 Accepted 07 November, 2013)

ABSTRACT: Voltage level control plays a significant role in ensuring the stable operation of power systems in the event of large disturbances and faults, and is thus a significant area of research. This paper investigates the improvement of Voltage level of a two-area multi-machine power system, using STATCOM (Static Synchronous Compensator), UPFC (unified power flow controller) which is an effective FACTS (Flexible AC Transmission System) device capable of controlling the active and reactive power flows in a transmission line by controlling appropriately parameters. Simulations are carried out in Matlab/Simulink environment for the two-area multi-machine power system model with STATCOM & UPFC to analyze the effects of UPFC, STATCOM on Voltage level improvement performance of the system. The simulation results demonstrate the effectiveness and robustness of the proposed STATCOM, UPFC on transient stability improvement of the system.

Keywords: UPFC, STATCOM, multi-machine power system model

I. INTRODUCTION

In recent years, the increase in peak load demand and power transfers between utilities has elevated concerns about system voltage security [1]. Power systems operation becomes more important as the load demand increases all over the world. This rapid increase in load demand forces power systems to operate near critical limits due to economical and environmental constraints. The objective in power systems operation is to serve energy with acceptable voltage and frequency to consumers at minimum cost. Reliability and security are also important parameters for power systems and should be satisfied. By reliability, it is meant that the system has adequate reserves in the face of changing energy demand. By security, it is meant that upon occurrence of a contingency, the system could recover to its original state and supply the same quality service as before. All these objectives can be achieved by proper planning, operation and control of power generation and transmission systems. Since generation and transmission units have to be operated at critical limits voltage stability problems may occur in power system when there is an increase in load demand. Voltage instability is one of the main problems in power systems. In voltage stability problem some or all buses voltages decrease due to insufficient power delivered to loads. In case of voltage stability problems, serious blackouts may occur in a considerable part of a system [2]. This can cause severe social and economic problems [2]. In fact, more than 50 cases of voltage instability or voltage collapse were reported all over the world between 1965 and 1996. For example, a voltage collapse in the North American Western Systems Coordinating Council system on July 2, 1996, resulted in service interruptions to more than 6 million people [2]. When the necessity of electricity to industry and community in all fields of the life is considered, the importance of a blackout can be understood more easily. Therefore, special analysis should be performed in order to examine the voltage stability in power systems [3]. The only way to save the system from voltage collapse is to reduce the reactive power load or add additional reactive power prior to reaching the point of voltage collapse [2]. Voltage collapse phenomena in power systems have become one of the important concerns in the power industry over the last two decades, as this has been the major reason for several major blackouts that have occurred throughout the world [4]. Point of collapse method and continuation method are used for voltage collapse studies [5]. Of these two techniques continuation power flow method is used for voltage analysis. These techniques involve the identification of the system equilibrium points or voltage collapse points where the related power flow Jacobian becomes singular [6-7]. The most common methods used in voltage stability analysis are continuation power flow, point of collapse, minimum singular value and optimization methods [3]. With the rapid development of power system, especially the increased use of transmission facilities due to higher industrial output and deregulation, it becomes necessary to explore new ways of maximizing power transfer in existing transmission facilities, while at the same time maintaining the acceptable levels of the network reliability and stability. On the other hand, the fast development of power electronic technology has made FACTS (flexible AC Transmission system) promising solution of future power system. FACTS controllers such as Static Synchronous Compensator (STATCOM), Static VAR Compensator (SVC), Thyristor Controlled Series Compensator (TCSC), Static Synchronous Series Compensator (SSSC) and Unified Power Flow controller (UPFC) are able to change the network parameters in a fast and effective way in order to achieve better system performance [8-11].

These controllers are used for enhancing dynamic performance of power systems in terms of voltage/angle stability while improving the power transfer capability and voltage profile in steady-state conditions [12-16]. Static VAR Compensator (SVC) is a FACTS controllers based on thyristor controlled reactor (TCRs), the first is a shunt compensator used for voltage regulation which is achieved by controlling the production, absorption and flow of reactive power through the network [17]. Unified Power Flow Controller (UPFC), is the most complete. It is able to control independently through active and reactive powers. The UPFC is capable to act over three basic electrical system parameters: line voltage, line impedance, and phase angle, which determine the transmitted power. Also Note that among the available FACTS devices, the Unified Power Flow Controller (UPFC) is the most versatile one that can be used to improve steady state stability, dynamic stability and transient stability [18].

In this study, continuation power flow method, widely used in voltage stability analysis, is utilized in order to analyze voltage stability of power systems. This paper described the concept of voltage stability phenomena .modeling of UPFC & STATCOM with and without PSS is presented. Results of system are also present in this paper.

In the past three decades, power system stabilizers (PSSs) have been extensively used to increase the system damping for low frequency oscillations. The power utilities worldwide are currently implementing PSSs as effective excitation controllers to enhance the system stability [2–22]. However, there have been problems experienced with PSSs over the years of operation. Some of these were due to the limited capability of PSS, in damping only local and not inter area modes of oscillations. In addition, PSSs can cause great variations in the voltage profile under severe disturbances and they may even result in leading power factor operation and losing system stability [23]. This situation has necessitated a review of the traditional power system concepts and practices to achieve a larger stability margin, greater operating flexibility, and better utilization of existing power systems.

II.VOLTAGE STABILITY

Power system stability can be divided into two as voltage stability and rotor angle stability. Rotor angle stability is the ability of interconnected synchronous machines of a power system to remain in synchronism [19]. In this kind of stability, power-angle equations are handled since power output of a synchronous machine varies as its rotor oscillates [2]. Voltage stability is the ability of a power system to maintain steady acceptable voltages at all buses in the system under normal operating conditions and after being subjected to a disturbance [19]. Voltage stability can be attained by sufficient generation and transmission of energy. Generation and transmission units have definite capacities that are peculiar to them. These limits should not be exceeded in a healthy power system. Voltage stability problem arises when the system is heavily loaded that causes to go beyond limitations of power system. A power system enters a state of voltage instability when a disturbance, increase in load demand power or change in system condition causes a progressive and uncontrollable decline in voltage. The main factor causing instability is the inability of the power system to meet the demand for reactive power [19].

a. Factors Affecting Voltage Stability: The main reason for voltage instability is the lack of sufficient reactive power in a system. Generator reactive power limits and reactive power requirements in transmission lines are the main causes of insufficient reactive power [20].

b. Reactive Power Limits of Generators: Synchronous generators are the main devices for voltage control and reactive power control in power systems. In voltage stability analysis active and reactive power capabilities of generators play an important role. The active power limits are due to the design of the turbine and the boiler. Therefore, active power limits are constant. Reactive power limits of generators are more complicated than active power limits. There are three different causes of reactive power limits that are; stator current, over-excitation current and under-excitation limits. The generator field current is limited by over-excitation limiter in order to avoid damage in field winding. In fact, reactive power limits are voltage dependent. However, in load flow programs they are taken to be constant in order to simplify analysis [20].

c. Transmission Lines: Transfer of active and reactive power is provided by transmission lines. Since transmission lines are generally long, transfer of reactive power over these lines is very difficult due to significant amount of reactive power requirement [2].

d. Voltage Collapse: Voltage collapse is the process by which the sequence of events accompanying voltage instability leads to a low unacceptable voltage profile in a significant part of system. When a power system is subjected to a sudden increase of reactive power demand, the required demand is met by the reactive power reserves supplied from generators and compensation devices. Most of the time, this can be achieved since there are sufficient reserves. Sometimes, it is not possible to meet this rapid increase in demand due to combination of events and system conditions. Thus, voltage collapse and a major breakdown of part or all of the system may occur [19]. There are some countermeasures that can be taken against voltage instability. Automatic voltage regulators (AVRs), under-load tap changers (ULTCs) and compensation devices are common ways to keep bus voltage magnitude in acceptable ranges [19].

III. STATIC SYNCHRONOUS COMPENSATOR (STATCOM)

The STATCOM is given this name because in a steady state operating regime it replicates the operating characteristics of a rotating synchronous compensator. The basic electronic block of a STATCOM is a voltage-sourced converter that converts a dc voltage at its input terminals into a three-phase set of ac voltages at fundamental frequency with controllable magnitude and phase angle.

A STATCOM can be used for voltage regulation in a power system, having as an ultimate goal the increase in transmittable power, and improvements of steady-state transmission characteristics and of the overall stability of the system. Under light load conditions, the controller is used to minimize or completely diminish line over voltage; on the other hand, it can be also used to maintain certain voltage levels under heavy loading conditions.

In its simplest form, the STATCOM is made up of a coupling transformer, a VSC, and a dc energy storage device. The energy storage device is a relatively small dc capacitor, and hence the STATCOM is capable of only reactive power exchange with the transmission system. If a dc storage battery or other dc voltage source were used to replace the dc capacitor, the controller can exchange real and reactive power with the transmission system, extending its region of operation from two to four quadrants. Figs.1 and 2 show a functional model and the V-I characteristic of a STATCOM respectively.

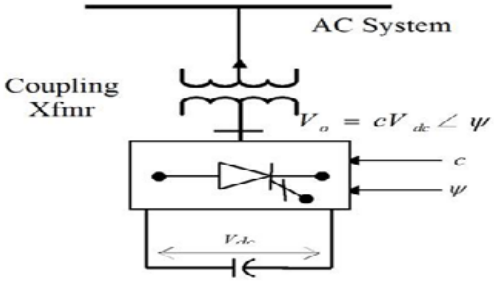

Fig.1. STATCOM Configuration.

The STATCOM's output voltage magnitude and phase angle can be varied. By changing the phase angle ψ of the operation of the converter switches relative to the phase of the ac system bus voltage, the voltage across the dc capacitor can be controlled, thus controlling the magnitude of the fundamental component of the converter ac output voltage, as $V_o = {}_cV_{dc}$

(i) POWER FLOW MODULATION. The STATCOM is modeled as a voltage-sourced converter behind a step down transformer as shown in Fig.1.

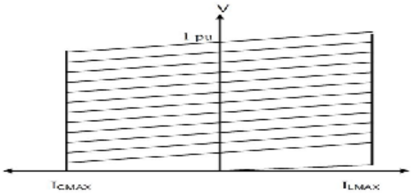

Fig. 2. STATCOM V-I characteristic.

The STATCOM generates a controllable AC-voltage source $V_{out}(t) = V_o \sin(\omega t - \psi)$behind the leakage reactance. The voltage difference between the STATCOM bus AC voltage and $V_{out}(t)$ produces active and reactive power exchange between the STATCOM and the power system.

$$V_O = cV_{DC}(\cos\psi + i\sin\psi) = cV_{DC} < \psi$$

$$dV_{DC}/dt = c/C_{DC}*(I_{LD}\cos\psi + I_{LQ}\sin\psi)$$

Where, for the PWM inverter, $c = mk$ and k is the ratio between AC and DC voltage; m is the modulation ratio defined by PWM, and ψ is defined by the PWM.

IV. UNIFIED POWER FLOW CONTROLLER

UPFC is a device placed between two buses referred to as the UPFC sending bus and the UPFC receiving bus. It consists of two voltage-source converters, as illustrated in Fig. 3. The back-to-back converters, labeled "shunt converter" and "series converter" in the Fig. 3, are operated from a common DC link provided by a DC storage capacitor. The shunt converter is primarily used to provide active power demand of the series converter through the common DC link. Shunt converter can also generate or absorb reactive power, if it is desired, and thereby it provides independent shunt reactive compensation for the line.

Series converter provides the main function of the UPFC by injecting a voltage with controllable magnitude and phase angle in series with the line. For the fundamental frequency model, the VSCs are replaced by two controlled voltage sources. The UPFC is placed on the high-voltage transmission lines. This arrangement requires step-down transformers in order to allow the use of power electronics devices for the UPFC. The UPFC can provide simultaneous control of all basic power system parameters (transmission voltage, impedance and phase angle). The controller can fulfill functions of reactive shunt compensation, series compensation and phase shifting, meeting multiple control objectives. From a functional perspective, the objectives are met by applying a DC capacitor, shunt connected transformer and voltage source converter in parallel branch and dc capacitor, voltage source convertor and series injected transformer in the series branch.

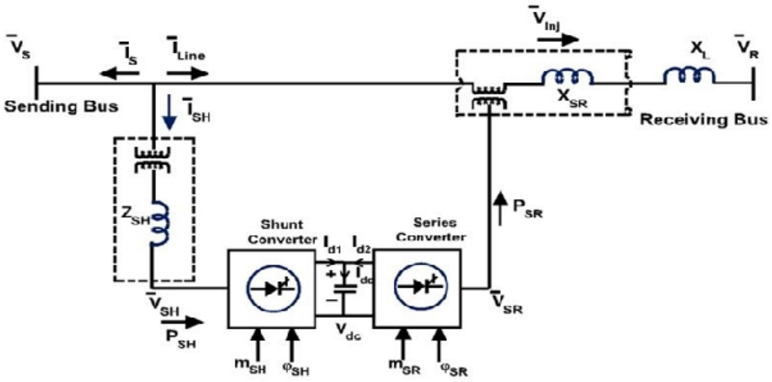

Fig. 3. UPFC Configuration.

The two voltage source converters area so called ”back to back” AC to DC voltage source converters operated from a common DC link capacitor, Fig.4. The shunt converter is primarily used to provide active power demand of the series converter through the common DC link. Converter 1 can also generate or absorb reactive power, if it is desired, and thereby provides independent shunt reactive compensation for the line. In fig.4; Converter 2 provides the main function of the UPFC by injecting a voltage with controllable magnitude and phase angle in series with the line. The reactance x_s describes the reactance seen from terminals of the series transformer and is equal to (in p.u. base on system voltage and base power)

$$Xs = x_k\, r^2_{max}(S_B/S_S) \quad \ldots.\ (1)$$

Where x_k denotes the series transformer reactance, r_{max} the maximum per unit value of injected voltage magnitude, S_B the system base power, and S_S the nominal rating power of the series converter. The UPFC injection model is derived enabling three parameters to be simultaneously controlled [23]. They are namely the shunt reactive power, Q_{conv1}, and the magnitude r, and the angle, γ, of injected series voltage V_{se}. Fig.5 shows the circuit representation of a UPFC, where the series connected voltage source is modelled by an ideal series voltage which is controllable in magnitude and phase, and the shunt converter is modelled as an ideal shunt current source. In Figure 6

$$\overline{I}_{sh} = \overline{I}_t + \overline{I}_q$$

$$\overline{I}_{sh} = (\overline{I}_t + j\overline{I}_q)e^{j\theta i} \quad ..\ (2)$$

Where I_t is the current in phase with V_i and I_q is the current in quadrature with V_i. In fig.5the voltage source V_{se} is replaced by the current source $I_{inj} = -jb_sV_{se}$ in parallel with x_s.

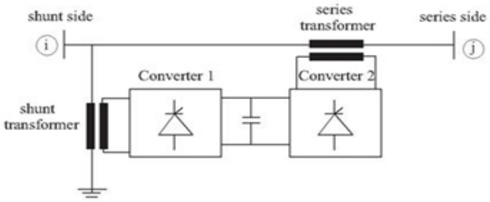

Fig. 4. Implementation of the UPFC by back-to-back voltage source converters.

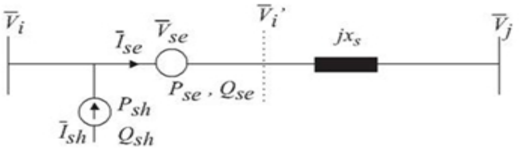

Fig. 5. The UPFC electric circuit arrangement.

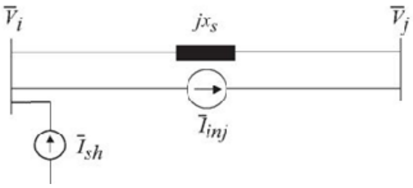

Fig. 6. Transformed series voltage source.

V. MULTIMACHINE POWER SYSTEM MODEL

A. Description of the Transmission System

The system consists of a two bus system as shown in Fig.7. The test system consists of four generators and three PQ bus (or load bus). system consists of the two buses which is connected to each other by the transmission line L_1, L_2 and L_3. Where L_1 = 150 km, L_2 = 150km and L_3 = 220km and four other transmission line used in the subsystem which is L_4 = 25 km, L_5 = 10 km, L_6 = 25 km, L_7 = 10 km. There are two area in the system in which round rotor generators rated 20KV/900MVA are used. In area 1 there is two generator which is G1and G_2.Where G_1=20kV/900MVA and G_2=KV/900 MVA. In area two there is also two generators which $G_3$and G_4. Where G_3=20KV/900MVA and G_4=20KV/900MVA.

Two three phases RLC and Capacitive load connected in area 1 and are 2. Here also used HTG Turbine and Regulators subsystems and power system stabilizer. After the load flow has been solved, the reference mechanical powers and reference voltages for the two machines have been automatically updated in the two constant blocks connected at the HTG and excitation system inputs:

V_{ref1} = 1.2 + 2, P_{ref1} = 0.95, V_{ref2} = 1, P_{ref2} = 0.7777,
V_{ref3} = 1, P_{ref3} = 0.79889, V_{ref4} = 1, P_{ref4} = 0.7778

B. System Analysis With-Out FACTS and PSS

The Two bus test system has been simulated here for voltage stability analysis, power transfer capability, rotor angle, terminal voltages of area1 and area 2 of the system. The analysis of system without FACTS is present here for comparative analysis of system performance. Fault occurred at 1 to 1.5 sec. The voltage and reactive power value at buses and the rotor angle deviation and speed of machine are measure by scope in simulation without FACTS. The simulation diagram is shown in Fig.7.

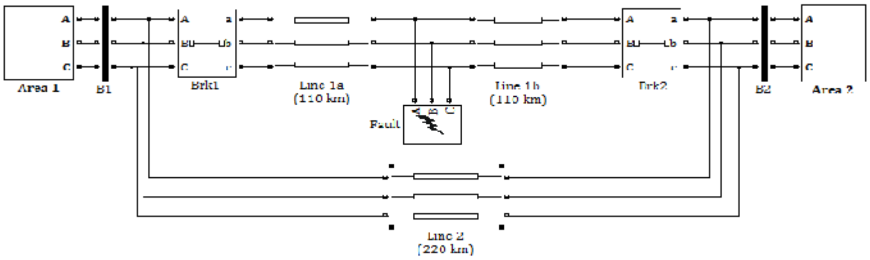

Fig. 7. Simulation of Test System without FACT Device & PSS.

C. Impact of STATCOM Without & With PSS

The Static Synchronous Compensator (STATCOM) is one of the key FACTS devices. STATCOM output current (inductive or capacitive) can be controlled independent of the AC system voltage. Impact of STACOM with and without PSS shown in Fig. 8 & 9.

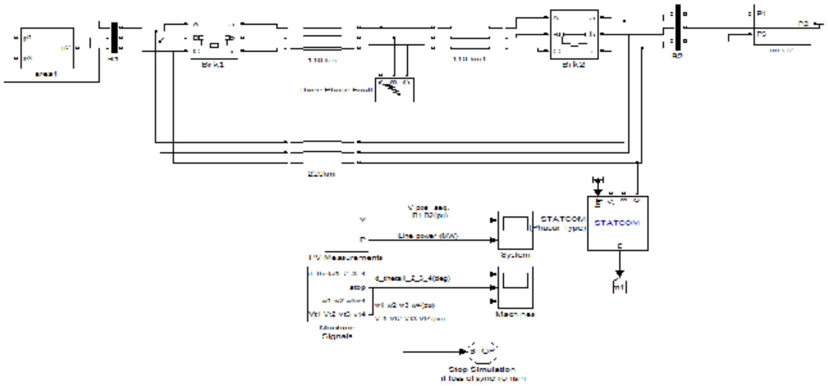

Fig. 8. Simulation of STATCOM Test System without PSS.

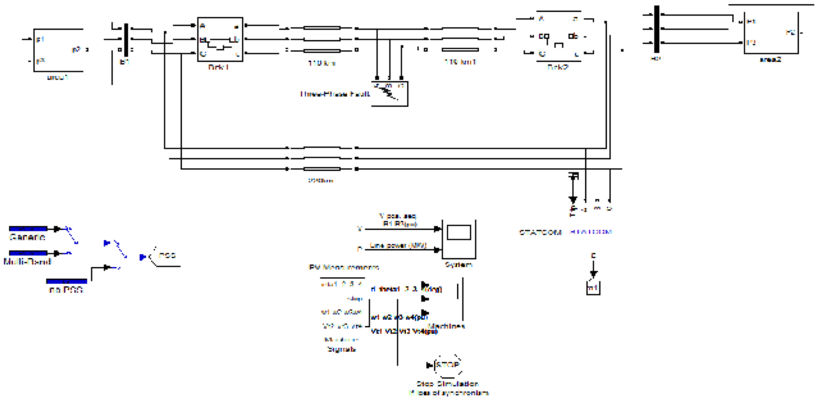

Fig. 9. Simulation of STATCOM Test System with PSS.

To control the oscillating swing in the multi machine system PSS must be connected in the system. Model of STATCOM with PSS Shown in fig. 9.

D. Impact of UPFC without & With PSS

The two-area system shown in Fig.10 is considered in this study. It is considered that a three phases to ground fault. UPFC placed between bus 4 &and bus five. Without a UPFC, the oscillations in generator rotor angle of Area- 1 and Area-2 increase and the settling time for the oscillations is found to be high. The oscillations in generator rotor angle of Area-1 and Area-2 decrease and the settling time for the oscillations is found to be slightly low. Hence, the transient stability of the two area power system is improved with UPFC. To control the oscillating swing in the multimachine system PSS must be connected in the system. Model of UPFC with PSS Shown in fig.11:

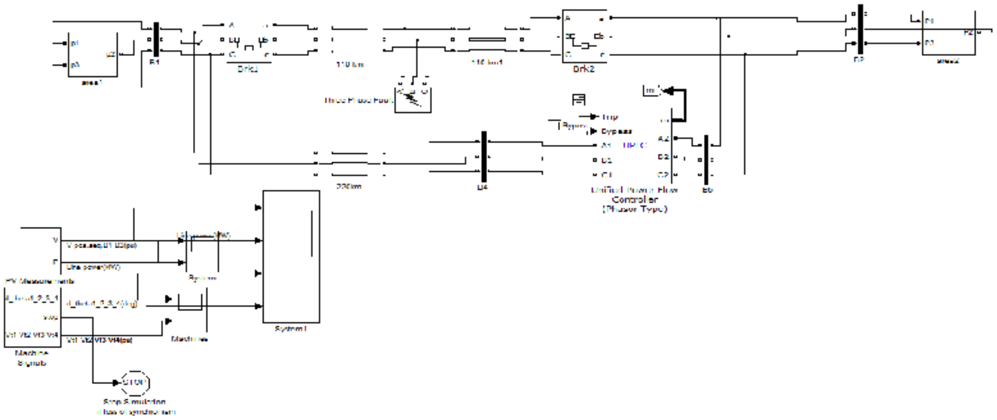

Fig.10. Two Area Multi Machine Model UPFC without PSS.

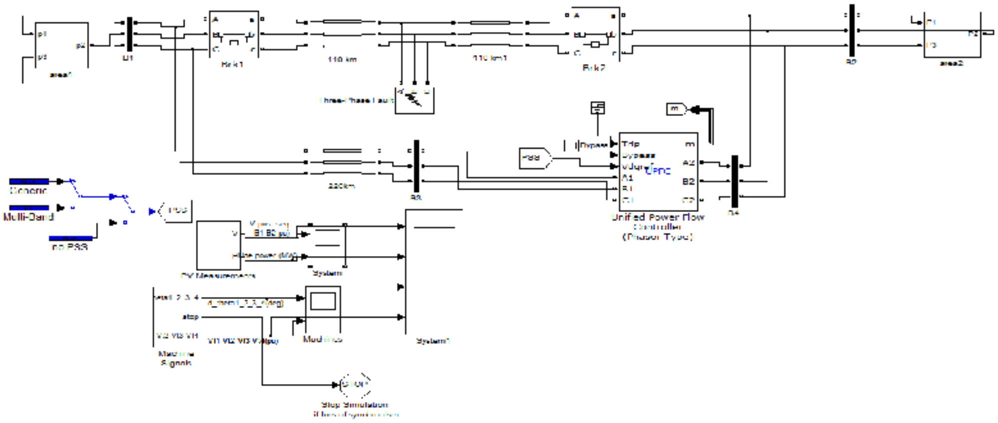

Fig.11. Two Area Multi Machine Model UPFC with PSS.

VI. SIMULATION RESULTS

A. Without FACTS and PSS

A result shows the two area multi machine system without PSS. In this results without FACTS device and PSS transient produced in system and settling time is very high. results of the bus voltage(B_1,B_2), line power, rotor angle deviation(δ), terminal voltages(v_{t1},v_{t2} v_{t3},v_{t4}) shown in Fig.12 &13. Three phases to ground fault occurred at 1 to 1.5 sec.

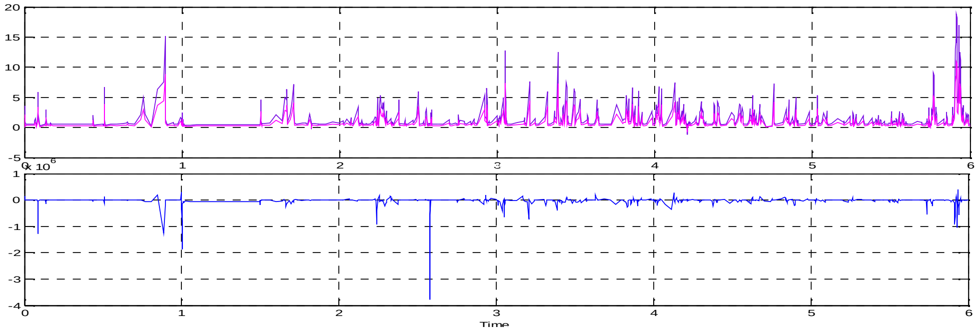

Fig. 12. Rotor Angle, Speed, Terminal Voltages v_{t1}, v_{t2}, v_{t3}, v_{t4}.

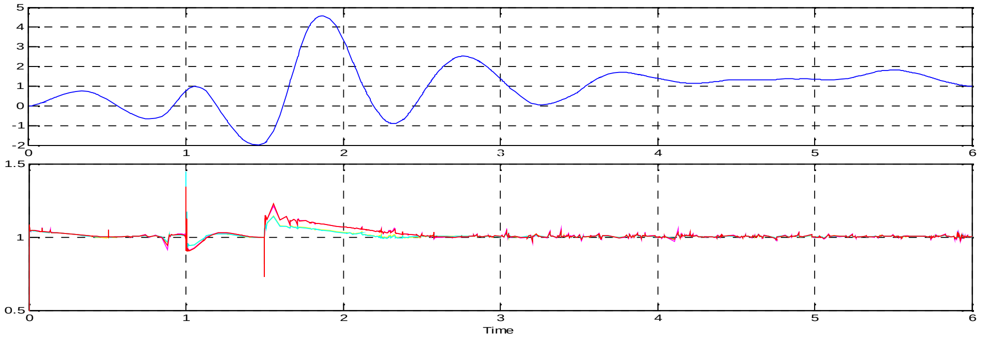

Fig. 13. Bus Voltages B_1, B_2 and Power.

B. STATCOM without PSS

In this system results transient reduce with the help of STATCOM. Bus voltage (B_1,B_2), line power (P), rotor angle deviation (δ), terminal voltages (v_{t1},v_{t2} v_{t3}, v_{t4}) is shown in Fig.14 & 15.Three phase to ground fault occurred at 1 to 1.5 sec.

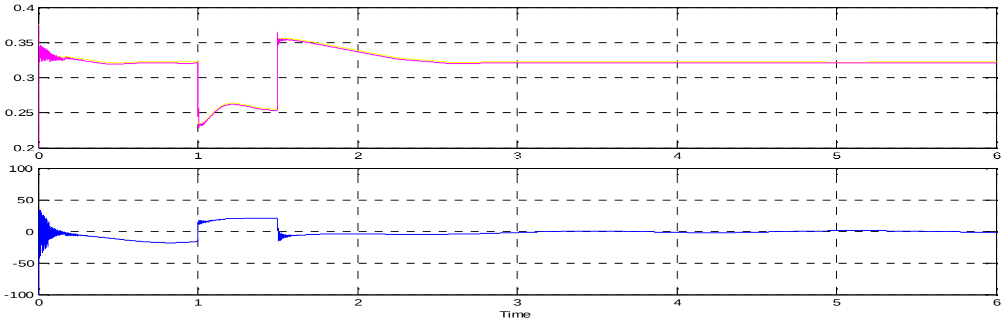

Fig. 14. Rotor Angle, Terminal Voltages v_{t1}, vt_2, v_{t3}, $v_{t4.}$

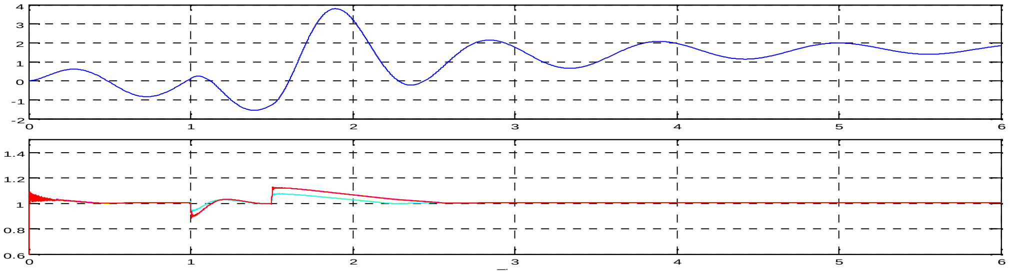

Fig.15. Bus Voltages B_1, B_2 and Power.

C. STATCOM with PSS

When PSS connected in the system the bus voltages and line power of system gives more stable results compare than without PSS. So the stability of system can improve by the use of PSS. When the PSS is connected in the system the system will become stable and transient will be reduce .mainly the oscillations in generator rotor angle deviation of area1 and area2 and line power stability can be improve by the use of PSS. Results of the bus voltage (B_1,B_2), line power ,rotor angle deviation(δ), terminal voltages (v_{t1},v_{t2} v_{t3}, v_{t4}) is shown in Fig.16 & 17. Three phases to ground fault occurred at 1 to 1.5 sec. Voltage stability during fault occurred in the system is much better than without PSS.

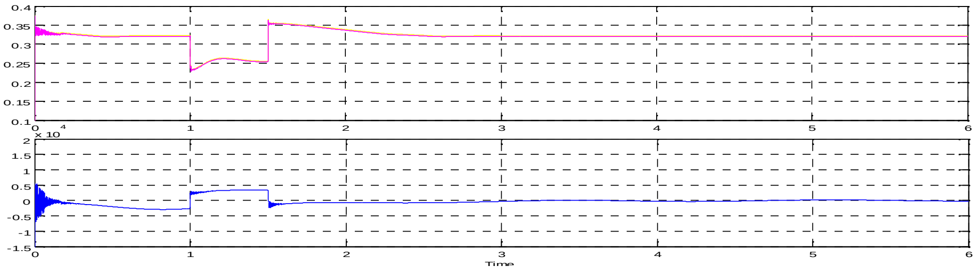

Fig.16. Rotor Angle, Terminal Voltages v_{t1}, v_{t2}, v_{t3}, $v_{t4.}$

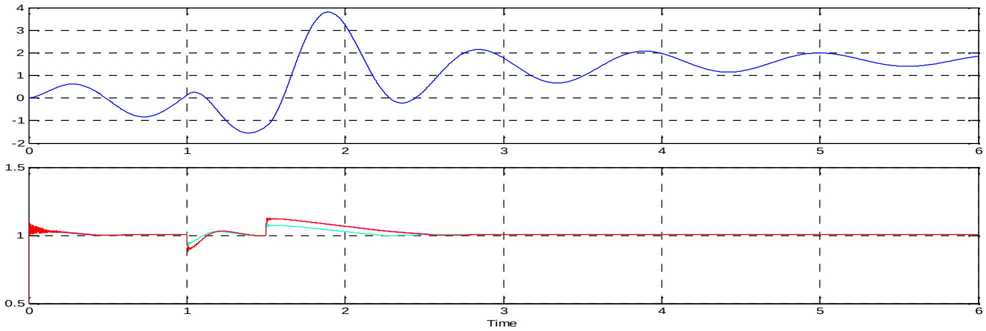

Fig.17. Bus Voltages B_1, B_2 and Power.

D. UPFC without PSS

The oscillations in generator rotor angle of Area-1 and Area-2 decrease and the settling time for the oscillations is found to be slightly low. Hence, the transient stability of the two area power system is improved with UPFC. Results of the bus voltage (B_1,B_2), line power , rotor angle deviation(δ), terminal voltages(v_{t1},v_{t2} v_{t3}, v_{t4}) is shown in Fig.18 & 19.

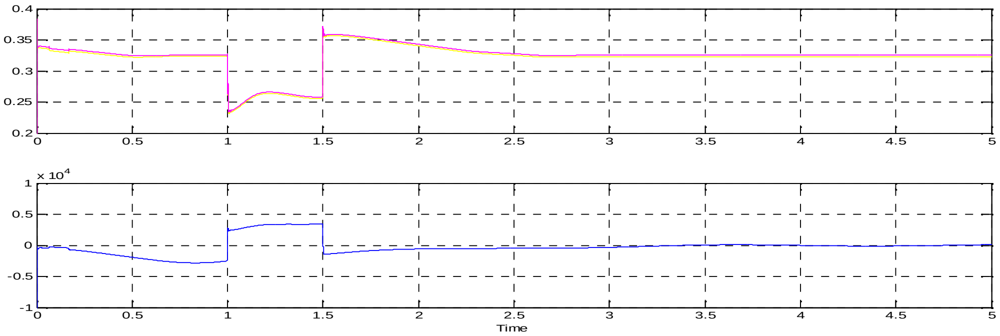

Fig. 18. Rotor Angle, Terminal Voltages v_{t1}, v_{t2}, v_{t3}, v_{t4}.

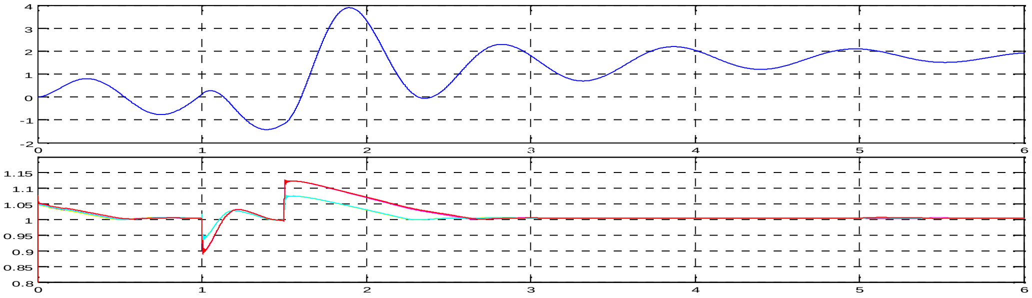

Fig. 19. Bus Voltages B_1, B_2 and Power.

E. UPFC with PSS

When PSS connected in the system the bus voltages and line power of system gives more stable results compare than without PSS. So the stability of system can improve by the use of PSS. When the PSS is connected in the system the system will become stable and transient will be reduce mainly the oscillations reduces in generator rotor angle deviation of area1 and area2 and line power stability can be improve by the use of PSS. Results of the bus voltage (B_1, B_2) line power, rotor angle deviation (δ), terminal voltages (v_{t1},v_{t2} v_{t3}, v_{t4}) is shown in Fig. 20 & 21. We can see that terminal voltage stability improve by the use of PSS.

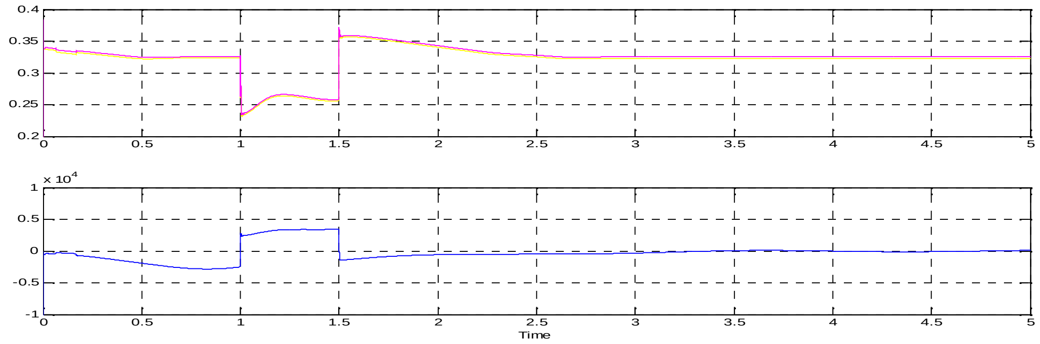

Fig. 20. Rotor Angle, Terminal Voltages v_{t1}, v_{t2}, v_{t3}, v_{t4}.

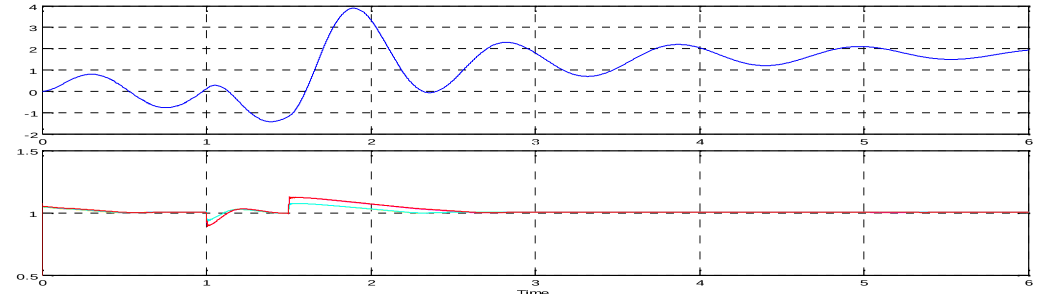

Fig. 21. Bus Voltages B_1, B_2 and Power.

VII. CONCLUSION

This Paper deals with applications of the STATCOM & UPFC. The detailed models of the STATCOM & UPFC were implemented and tested in MATLAB/simulink environment. The models are applicable for voltage stability analysis, and cover broader range of power transfer capability. The effects of FACTS (STATCOM & UPFC) installed in power transmission path are analyzed in this paper, and the conclusions are as follow:

(i) The UPFC give superior performance than STATCOM for reactive power, voltages and power transfer capability for two area multi machine power systems.

(ii) Similarly the performance enhancement of two area multi machine test system can be analyses for compensate reactive power, voltage injected and increased power transfer capability.

(iii) The best performance has been obtained by introducing FACTS devices such as SVC and STATCOM which compensate reactive power (MVAR), voltage injected (kV) and increased power transfer capability (MVA). It's concluded that by introducing FACTS device system performance, voltage stability and transmission capability improves considerably.

REFERENCES

[1]. V. Ajjarapu and C. Christy, “The continuation power flow: A tool for steady state voltage stability” Trans. on Power Systems, vol. **7**, no. 1, pp.426-423, Feb.1992

[2]. M. Larsson, "Coordinated Voltage Control in Electric Power Systems, “Doctoral Dissertation”, Lund University 2000.

[3]. Mehmet B. Kesk_n, “Continuation Power Flow and Voltage Stability in Power Systems”, A Thesis Submitted to the Graduate School of Natural and Applied Sciences of Middle East Technical University, Sep 2007.

[4]. Blackout of 2003: Description and Responses, Available: http://www.pserc.wisc.edu/.

[5]. R. Natesan and G. Radman," Proceedings of the system theory thirty- Sixth southeastern symposium”, pp. 546-550, 2004.

[6]. Dobson and H. D. Chiang, “Towards a theory of Voltage collapse in electric power systems”, *Systems & Control Letters*, vol.**13**,1989,pp.253-262

[7]. C. A. Canizares, F. L. Alvarado, C. L. DeMarco, I. Dobson, and W. F.Long, “Point of collapse methods applied to acldc power systems”, *IEEE Trans. Power Systems*,vol.**7**, no. 2, pp. 673-683, May 1992.

[8]. N.G. Hingorani, L. Gyugyi, “Understanding FACTS: Concepts and Technology of Flexible ac Transmission Systems”, IEEE Press New York, 1999.

[9]. Enrique Acha *et al*., “FACTS: Modeling and Simulation in Power Networks”, Wiley, 2004.

[10]. A. Edris, "FACTS technology development: an *update IEEE Eng. Rev.* **20**(3), pp.4-9, 2000.

[11]. R. Mohan Marthur and Rajiv K.Varma, “Thyristor Based-FACTS controllers for electrical transmission systems” Wiley, 2002.

[12]. Kirschner L.; Retzmann D.; Thumm G.; Benefits of FACTS for PowerSystemEnhancement", Transmission and Distribution Conference andExhibition: Asia and Pacific, 2005 IEEE/PES, pp.1-7.

[13]. Yan Ou; ChananSingh, "Improvement of total transfer capability using TCSC and SVC", Power Engineering Society, 2001.IEEE,Volume **2**, July 2001, pp: 944-948.

[14]. Perez M.A., Messina A.R. , Fuerte Esquivel C.R. "Application of FACTS devices to improve steady state voltage stability," Power Engineering Society Summer Meeting, 2000. *IEEE*, Volume **2**, July 2000, pp.1115-112.

[15]. Xingbin Yu; Chanan Singh; Jakovljevic S.; Ristanovic D.; GarngHuang, "Total transfer capability considering FACTS and security constraints", "Transmission and Distribution Conference and Exposition", 2003 IEEE PES , Volume **1**,7-12,pp.73–78, 2003.

[16]. Pilotto L.A.S., Ping W.W., Carvalho A.R., Wey A., Long W.F,. Alvarado F.L., Edris A, "Determination of needed FACTS controllers that increase asset utilization of power systems". Power Delivery, *IEEE Transactions on* Volume: **12**, Issue: 1, pp; 364-371, Jan.1997.

[17]. Mohammed Osman Hassan, S. J. Cheng, Senior Member, IEEE, Zakaria Anwar Zakaria, "Steady-State Modeling of SVC and TCSC for Power Flow Analysis", IMECS 2009, Hong Kong, March 18 - 20, 2009.

[18]. Hadisaadat, (Book style), Power System Analysis, McGraw Hill International editions.

[19]. P. Kundur, "Power System Stability and control, MC Graw Hill.

[20]. S. Repo, "On-line Voltage Stability Assesment of Power System, An Approach of Black-box Modelling", Tampere University of Technology Publications #344, 2001.

[21]. Y.N. Yu, Electric Power System Dynamics. Academic Press, 1983.

[22]. J. Paserba, Analysis and Control of Power System Oscillations. CIGRE Final Report, Task Force 07, Advisory Group 01, Study Committee **38**, 1996.

[23]. A. H. M. A. Rahim and S. G. A. Nassimi, "Synchronous Generator Damping Enhancement through Coordinated Control of Exciter and SVC", *IEE Proc. Genet. Transm. Distrib*., **143**(2)(1996), pp. 211–218.

[24]. North American Electric Reliability Council, "Available transfer capability definitions and determination", www.nerc.com, June 1996.