Transient Stability Analysis with SVC and STATCOM in Multi-Machine Power Systems with and without PSS using Matlab/Simulink

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Abstract **: The objective of this paper is to analyze the performance of a static var compensator and static synchronous compensator with and without power system stabilizer(PSS). To illustrate the performance of the FACTS(Flexible AC Transmission systems) controller SVC and STATCOM with and without PSS, IEEE three machines, nine bus Multi-Machine power System has been considered. The designed system tested using matlab simulink software and result was compared. The simulation was run for 10 seconds. Time domain simulation method is implemented in this paper. STATCOM showed better improvement in transient stability compare with SVC. The performance was also compared with GPSS(Generic Power system Stabilizer) and MBPSS Multiband Power System Stabilizer) to see the effect of further oscillations created during and after fault in the system with SVC and STATCOM. The MBPSS showed better effect than GPSS to damp the further oscillations created in the system during and after fault with SVC and STATCOM.**

Keywords : Transient Stability, SVC, STATCOM, GPSS, MBPSS, Matlab/Simulink

1. Introduction:

The power demand depends on load demand. If active power demand increases then speed of generators drop down and frequency of EMF decreases. If the reactive power demand increases then speed does not get affected but it is the magnitude of voltage which decreases. Thus load demand can make generators unstable. If load changes are small and stability is maintained, it is called as steady state stability. If load changes are large and sudden, still stability is maintained, it is transient stability. Stability must be maintained under any circumstances to have uninterrupted power supply. Stability is the response of the Synchronous Generator, supplying power to the external network following a disturbance. Under steady operation, it runs at Synchronous speed and when there is a perturbation, small or large, then machine tends to swing. It may either get restored to its original state or new state or fall out of step. Thus, transient stability is defined as the ability of the power system to maintain synchronism when subjected to a severe transient disturbance, such as a fault on transmission facilities, sudden loss of generation, or loss of a large load. The resulting system response involves large excursions of generator rotor angles and is influenced by the nonlinear power-angle relationship. Transient stability depends on both the initial operating state of the system and the severity of the disturbance. The transient stability can further be divided into two classes i) First-Swing Stability: for first one second after a system fault (simple generator model & no control model). ii) Multi Swing Stability: system analysis over long period of time (more sophisticated machine model) [1,2]. To reduce the effect of transient stability and oscillations created in the power systems during and after faults, flexible AC transmission systems (FACTS) controllers and power system stabilizers are used in the system. FACTS controllers are capable of controlling the network condition in a very effective manner and this feature of FACTS can be exploited to improve the voltage stability, steady state and transient stabilities of a complex power system. This allows increased utilization of existing network closer to its thermal loading capacity, and thus avoiding the need to construct new transmission lines. In this paper SVC and STATCOM phasor type models are used for study [3,4]. Due to excitation and system parameter combinations under certain loading conditions can introduce negative damping into the system. In order to offset this effect and to improve system damping in general, artificial means of producing torques in phase with the speed are introduced. These are called supplementary stabilizing signals and the networks used to generate these signals are known as power system stabilizers [2]. Power System Stabilizer (PSS) is a feedback controller, for a synchronous generator which provides an additional stabilizing signal to Automatic Voltage Regulator (AVR) through voltage reference input in order to damp out Low Frequency Oscillations (LFO). The purpose of PSS is to damp out the generator rotor oscillation in the range of 0.1 to 3 Hz. To damp out the electromechanical oscillations, PSS is expected to produce an electrical torque components should be in phase with rotor speed deviation of the generator. There are two types of stabilizer (i) Generic power system stabilizer model using the acceleration power (Pa= difference between mechanical power Pm and output electrical power Peo) and a (ii) Multi-band power system stabilizer using the speed deviation (dw) [17,23].

2. Power System Stablizer (PSS) Models

2.1. Generic Power System Stabilizer

The Generic Power System Stabilizer (PSS) block can be used to add damping to the rotor oscillations of the synchronous machine by controlling its excitation. The disturbances occurring in a power system induce electromechanical oscillations of the electrical generators. These oscillations, also called power swings, must be effectively damped to maintain the system stability. The output signal of the PSS is used as an additional input (vstab) to the Excitation System block. The PSS input signal can be either the machine speed deviation, dw, or its acceleration power, Pa = Pm - Peo (difference between the mechanical power and the electrical power). The Generic Power System Stabilizer is modeled by the following nonlinear system:

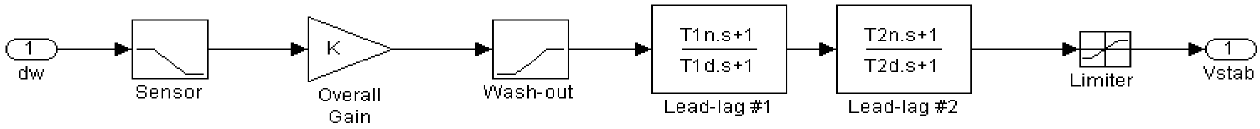

Figure 1. The Block Diagram of the Generic Power System Stabilizer

Figure 1 shows the block diagram of the generic power system stabilizer (PSS), which can be modeled by using the following transfer function:

$G(s) = K *[(T_{1n}.S + 1)(T_{2n}.S +1) / (T_{1d}.S+1)(T_{2d}.S+1)]$ (1)

To ensure a robust damping, the PSS should provide a moderate phase advance at frequencies of interest in order to compensate for the inherent lag between the field excitation and the electrical torque induced by the PSS action. The model consists of a low-pass filter, a general gain, a washout high-pass filter, a phase-compensation system, and an output limiter. The general gain *K* determines the amount of damping produced by the stabilizer. The washout high-pass filter eliminates low frequencies that are present in the *dw* signal and allows the PSS to respond only to speed changes. The phase-compensation system is represented by a cascade of two first-order lead-lag transfer functions used to compensate the phase lag between the excitation voltage and the electrical torque of the synchronous machine[5,9].

2.2. Multi-band Power System Stabilizer

The disturbances occurring in a power system induce electromechanical oscillations of the electrical generators. These oscillations, also called power swings, must be effectively damped to maintain the system's stability. Electromechanical oscillations can be classified in four main categories [1, 3, 4]:

(1) Local oscillations: between a unit and the rest of the generating station and between the latter and the rest of the power system. Their frequencies typically range from 0.8 to 4.0Hz.

(2) Interplant oscillations: between two electrically close generation plants. Frequencies can vary from 1 to 2Hz.

(3) Interarea oscillations: between two major groups of generation plants. Frequencies are typically in a range of 0.2 to 0.8Hz.

(4) Global oscillation: characterized by a common in-phase oscillation of all generators as found on an isolated system. The frequency of such a global mode is typically under 0.2Hz.

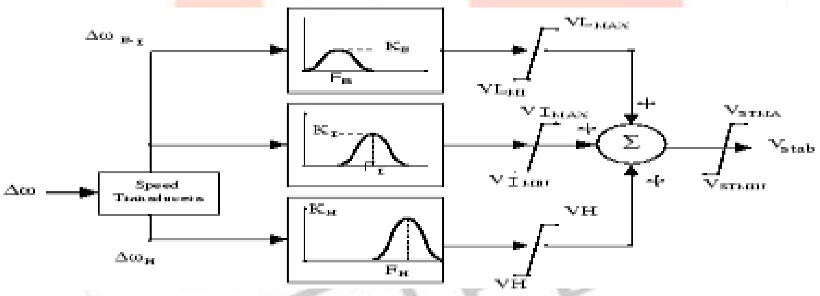

Figure 2. The Block Diagram of the Multi-band Power System Stabilizer (MB-PSS)

The need for effective damping of such a wide range, almost two decades, of electromechanical oscillations motivated the concept of the multiband power system stabilizer (MBPSS), as shown in Figure 2. Just as its name reveals, the MB-PSS structure is based on multiple working bands. Three separate bands are dedicated to the low-, intermediate-, and high-frequency modes of oscillations: the low band is typically associated with the power system global mode, the intermediate with the interarea modes, and the high with the local modes. Each of the three bands is made of a differential bandpass filter, a gain, and a limiter. The outputs of the three bands are summed and passed through a final limiter producing the stabilizer output *Vstab*. This signal then modulates the set point of the generator voltage regulator so as to improve the damping of the electromechanical oscillations. To ensure robust damping, the MB-PSS should include a moderate phase advance at all frequencies of interest to compensate for the inherent lag between the field excitation and the electrical torque induced by the MB-PSS action[8,9].

3. Static Var Compensator (SVC)

Figure 3 shows the single-line diagram of a static var compensator and its control system. The variation of reactive power is performed by switching three-phase capacitor banks and inductor banks connected on the secondary side of a coupling transformer. Each capacitor bank is switched on and off by three thyristor switches (Thyristor Switched Capacitor or TSC). Reactors are either switched on-off (Thyristor Switched Reactor or TSR) or phase-controlled (Thyristor Controlled Reactor or TCR).

The control system consists of the following issues:

(1) A measurement system measuring the positive-sequence voltage is to be controlled.

(2)A Fourier-based measurement system using a one-cycle running average is used.

(3) A voltage regulator that uses the voltage error (difference between the measured voltage Vm and the reference voltage Vref) to determine the SVC susceptance B needed to keep the system voltage constant.
(4) A distribution unit that determines the TSCs (and eventually TSRs) must be switched in and out, and computes the firing angle of TCRs.
(5) A synchronizing system using a phase-locked loop (PLL) synchronized on the secondary voltages and a pulse generator that send appropriate pulses to the thyristors[5,9,24].

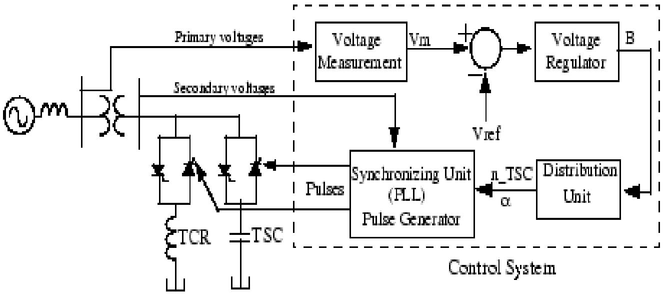

Figure 3. The Single-Line Diagram of a Static Var Compensator and its Control System.

3.1. SVC V-I Characteristic

The SVC can be operated in two different modes: In voltage regulation mode (the voltage is regulated within limits as explained below). In var control mode (the SVC susceptance is kept constant). When the SVC is operated in voltage regulation mode, it implements the following V-I characteristic (Figure 4).

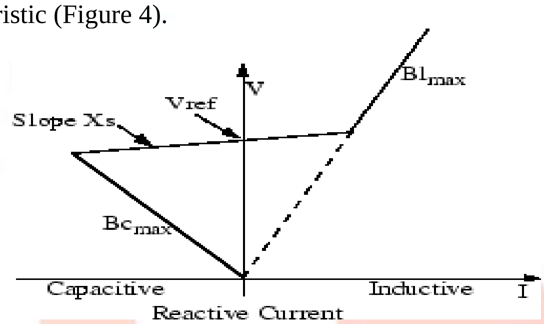

Figure 4. The V-I Characteristics of the SVC

As long as the SVC susceptance (*B*) stays within the maximum and minimum susceptance values imposed by the total reactive power of capacitor banks (*Bcmax*) and reactor banks (*Blmax*), the voltage is regulated at the reference voltage *Vref*. However, a voltage droop is normally used (usually between 1% and 4% at maximum reactive power output), and the *V-I* characteristic has the slope indicated in the Figure. The *V-I* characteristic is described by the following three equations[1, 3, 4]:

$V = V_{ref} + Xs \cdot I$ {if SVC is in regulation range ($-Bc_{max} < B < Bl_{max}$)} (2)

$V = -(I / Bc_{max})$ { If SVC is fully capacitive ($B = Bc_{max}$)} (3)

$V = I / Bl_{max}$ { If SVC is fully inductive ($B = Bl_{max}$) } (4)

Where, V = Positive sequence voltage, I = Reactive current(pu/Pbase) (I > 0 indicates an inductive current)
Xs = Slope or droop reactance (pu/Pbase),
Bcmax = Maximum capacitive susceptance(pu/Pbase) with all
TSCs in service, no TSR or TCR
Blmax = Maximum inductive susceptance(pu/Pbase) with all TSRs or TCRs at full conduction, no TSC.
Pbase = Three –phase base power[9].

3.2. SVC Dynamic Response

When the SVC is operating in voltage regulation mode, its response speed to a change of system voltage depends on the voltage regulator gains (proportional gain Kp and integral gain Ki), the droop reactance Xs, and the system strength (short-circuit level).
For an integral-type voltage regulator (Kp = 0), if the voltage measurement time constant Tm and the average time delay Td due to valve firing are neglected, the closed-loop system consisting of the SVC and the power system can be approximated by a first-order system having the following closed-loop time constant:

$T_c = 1 / [Ki(Xs + Xn)]$ (5)

Where, '*T c*' represents the closed-loop time constant; '*K i*' represents the proportional gain of the voltage regulator (p.u._B/p.u._V/s); '*X s*' represents the slope reactance p.u./Pbase; '*X n*' represents the equivalent power system reactance (p.u./Pbase).

This equation demonstrates that we obtain a faster response speed when the regulator gain is increased or when the system short-circuit level decreases (higher *Xn* values). If we take into account the time delays due to voltage measurement system and valve firing, we obtain an oscillatory response and, eventually, instability with too weak a system or too large a regulator gain[9].

4. Static Synchronous Compensator (STATCOM)

The Static Synchronous Compensator (STATCOM) is a shunt device of the Flexible AC Transmission Systems (FACTS) family using power electronics to control power flow and improve transient stability on power grids. The STATCOM regulates voltage at its terminal by controlling the amount of reactive power injected into or absorbed from the power system. When system voltage is low, the STATCOM generates reactive power (STATCOM capacitive). When system voltage is high, it absorbs reactive power (STATCOM inductive)[9,13].

The variation of reactive power is performed by means of a Voltage-Sourced Converter (VSC) connected on the secondary side of a coupling transformer. The VSC uses forced-commutated power electronic devices (GTOs, IGBTs or IGCTs) to synthesize a voltage V2 from a DC voltage source. The principle of operation of the STATCOM is explained on the figure below showing the active and reactive power transfer between a source V1 and a source V2. In this figure, V1 represents the system voltage to be controlled and V2 is the voltage generated by the VSC[9,13].

4.1 Operating Principle of the STATCOM

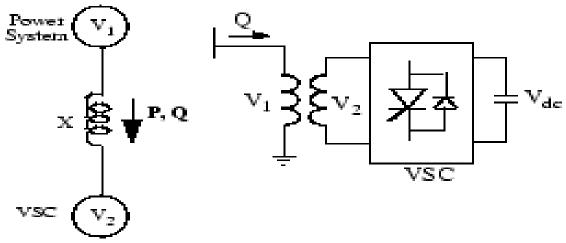

Figure 5. Basic functional model of STATCOM

$P = (V_1V_2)\sin\delta / X$, $Q = V_1(V_1 - V_2\cos\delta) / X$ (6)

V1 = Line to line voltage of source1, V2 = Line to line voltage of source2, X = Reactance of interconnection transformer and filters, δ = Phase angle of V_1 with respect to V_2

In steady state operation, the voltage V2 generated by the VSC is in phase with V1 (δ=0), so that only reactive power is flowing (P=0). If V2 is lower than V1, Q is flowing from V1 to V2 (STATCOM is absorbing reactive power). On the reverse, if V2 is higher than V1, Q is flowing from V2 to V1 (STATCOM is generating reactive power). The amount of reactive power is given by $Q = (V_1(V_1 - V_2)) / X$. (7)

A capacitor connected on the DC side of the VSC acts as a DC voltage source. In steady state the voltage V2 has to be phase shifted slightly behind V1 in order to compensate for transformer and VSC losses and to keep the capacitor charged. Two VSC technologies can be used for the VSC:

- VSC using GTO-based square-wave inverters and special interconnection transformers. Typically four three-level inverters are used to build a 48-step voltage waveform. Special interconnection transformers are used to neutralize harmonics contained in the square waves generated by individual inverters. In this type of VSC, the fundamental component of voltage V2 is proportional to the voltage Vdc. Therefore Vdc has to be varied for controlling the reactive power.
- VSC using IGBT-based PWM inverters. This type of inverter uses Pulse-Width Modulation (PWM) technique to synthesize a sinusoidal waveform from a DC voltage source with a typical chopping frequency of a few kilohertz. Harmonic voltages are cancelled by connecting filters at the AC side of the VSC. This type of VSC uses a fixed DC voltage Vdc. Voltage V2 is varied by changing the modulation index of the PWM modulator[9,15,22,24,].

4.2 Single-line Diagram of a STATCOM and Its Control System Block Diagram

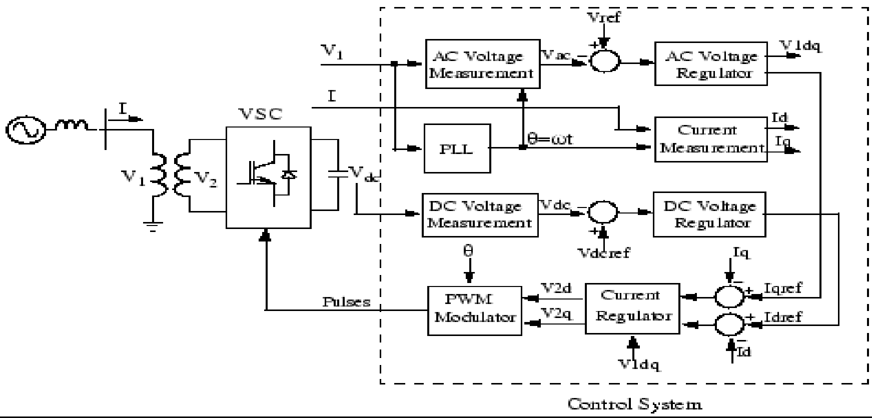

Figure 6. Single-line Diagram of a STATCOM and Its Control System Block Diagram

The control system consists of: A phase-locked loop (PLL) which synchronizes on the positive-sequence component of the three-phase primary voltage V1. The output of the PLL (angle $\Theta=\omega t$) is used to compute the direct-axis and quadrature-axis components of the AC three-phase voltage and currents (labeled as Vd, Vq or Id, Iq on the diagram).

- Measurement systems measuring the d and q components of AC positive-sequence voltage and currents to be controlled as well as the DC voltage Vdc.
- An outer regulation loop consisting of an AC voltage regulator and a DC voltage regulator. The output of the AC voltage regulator is the reference current Iqref for the current regulator (Iq = current in quadrature with voltage which controls reactive power flow). The output of the DC voltage regulator is the reference current Idref for the current regulator (Id = current in phase with voltage which controls active power flow).
- An inner current regulation loop consisting of a current regulator. The current regulator controls the magnitude and phase of the voltage generated by the PWM converter (V2d V2q) from the Idref and Iqref reference currents produced respectively by the DC voltage regulator and the AC voltage regulator (in voltage control mode). The current regulator is assisted by a feed forward type regulator which predicts the V2 voltage output (V2d V2q) from the V1 measurement (V1d V1q) and the transformer leakage reactance[9,21,23].

4.3 STATCOM V-I Characteristic

The STATCOM can be operated in two different modes:

- In voltage regulation mode (the voltage is regulated within limits as explained below)
- In var control mode (the STATCOM reactive power output is kept constant)

When the STATCOM is operated in voltage regulation mode, it implements the following V-I characteristic.

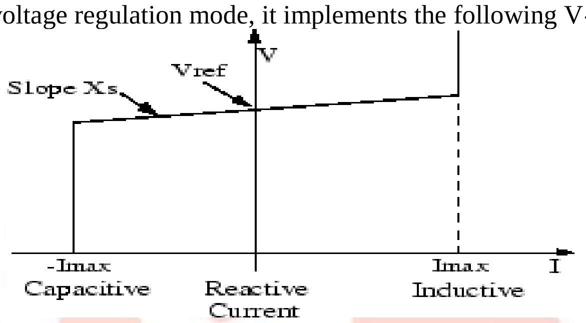

Figure 7. The V-I Characteristics of the STATCOM

As long as the reactive current stays within the minimum and minimum current values (-Imax, Imax) imposed by the converter rating, the voltage is regulated at the reference voltage Vref. However, a voltage droop is normally used (usually between 1% and 4% at maximum reactive power output), and the V-I characteristic has the slope indicated in the figure. In the voltage regulation mode, the V-I characteristic is described by the equation: $V = V_{ref} + Xs\, I$ (8)

Where, V = Positive sequence voltage (pu), I = Reactive current (pu/Pnom) (I > 0 indicates an inductive current), Xs = Slope or droop reactance (pu/Pnom), Pnom = Three-phase nominal power of the converter[9,15,22].

6. Simulation Model and Results:

Matlab software is used for analysis of transient stability of the multi-machine, IEEE 9-bus bar power system network with SVC and STATCOM which are connected between bus 4 and bus 5 as shown in figure 8 & 9. The three machines are equipped with a hydraulic turbine and governor(HTG), excitation system and power system stabilizer(PSS). Both SVC and STATCOM used for this model have same rating of +/- 200 MVA and the reference voltage is set to 1 per unit(pu) for both SVC and STATCOM. Here, generator G1 capacity of 800 MVA/13.8 kV is connected to slack bus 1, whereas generators G2 of 700MVA/13.8 kV and G3 of 300MVA/13.8 kV are connected to bus bars 2 and 3, respectively. The system has three transformers with 13.8/500 KV each, respectively. It comprises of three loads, load A with 400 MW 300 MVAR, load B with 500 MW 300 MVAR and load C with 200 MW 300 MVAR connected at buses 5, 6 and 8 respectively. The transmission system is of 500 KV. The base MVA of the system is 100 and system frequency is 60 Hz. All the time constants are in seconds. The transient stability analysis has been carried out by monitoring the performance of the generators (G1, G2 and G3) and different buses. Figure no. 10, shows the waveforms of without three phase fault, here the system is stable so does not required facts and pss devices in this case The transient stability analysis of this power system network have been considered when three phase fault occurs at bus 7 at time t = 0.25s and cleared at 1.5s. The total duration of fault is 1.25s. It is observed that the system quickly losses its stability after fault clearing as shown in figure11. In order not to pursue unnecessary simulation, the Simulink Stop block is used to stop the simulation when angle difference reaches 3*360.. During & post fault condition shown in fig 12 to 17, The terminal voltage and speed of all generators was observed. The terminal voltage reached to zero pu during fault and increased up to 1.8 pu and settled at 1 pu after fault. During fault, speed of all generators increased up to 1.1 pu due to sudden decrease in load and settled at 1 pu after fault.

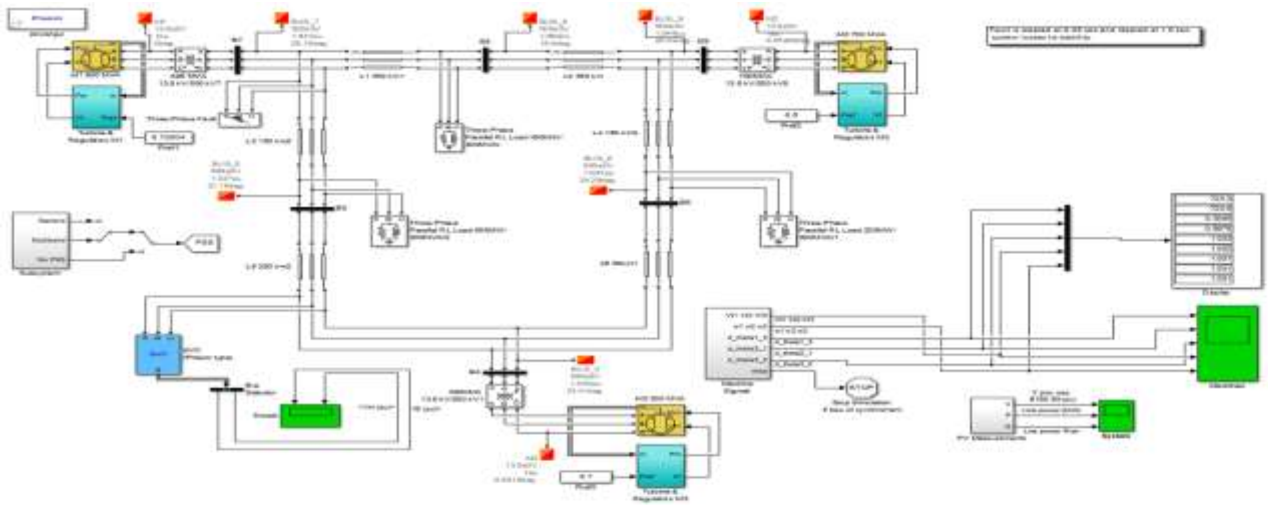

Figure8. Simulink model of 3 machine 9 bus system with SVC

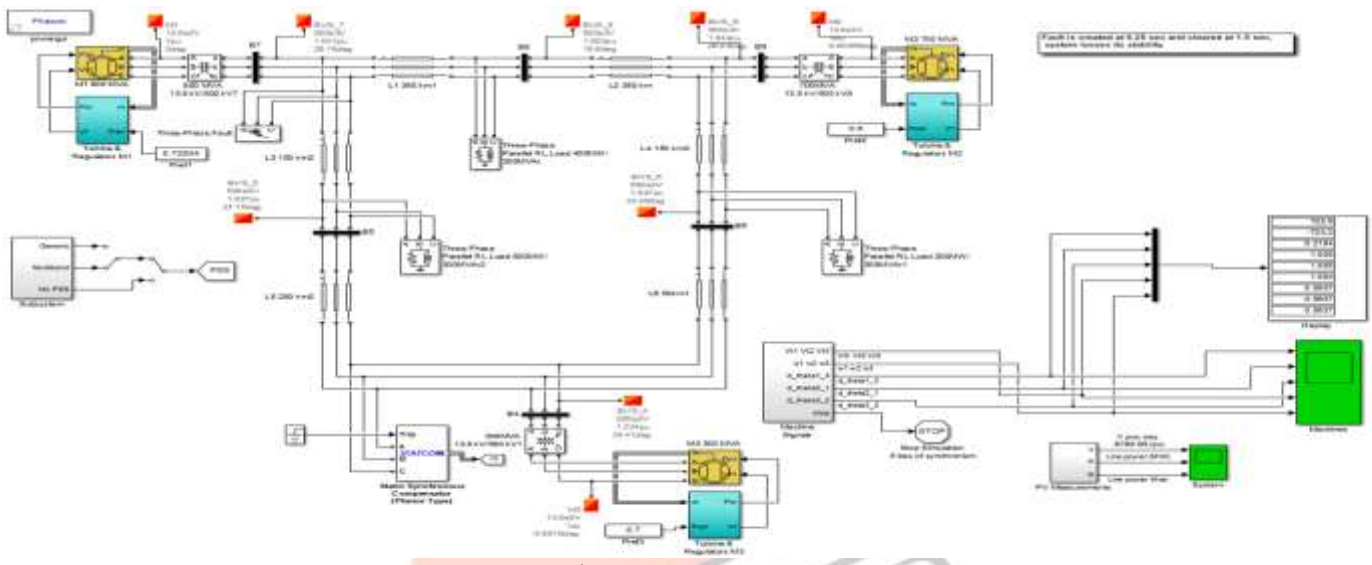

Figure9. Simulink model of 3 machine 9 bus system with STATCOM

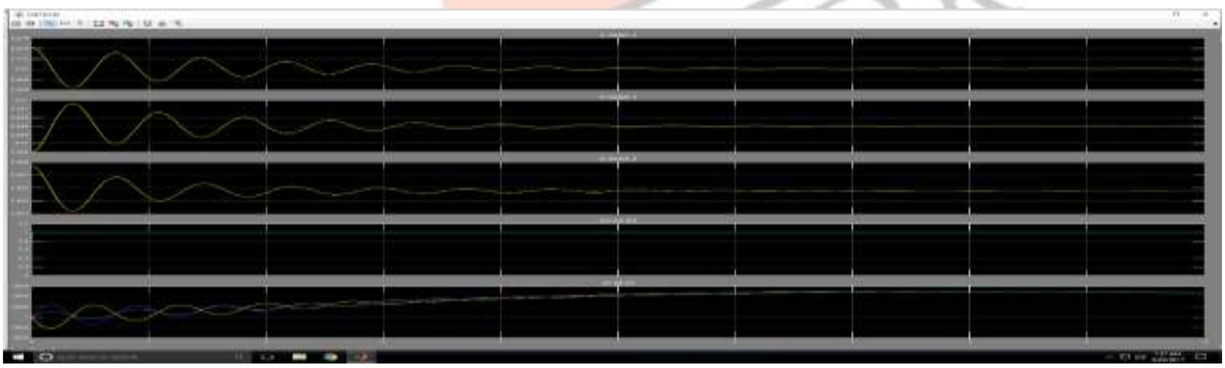

Figure10. Waveform of without three phase fault – (i) Rotor angle deviation between generator G1,G2 and G3 (ii) Speed of rotor machine G1, G2 and G3 (iii) Stator Voltage of G1, G2 and G3

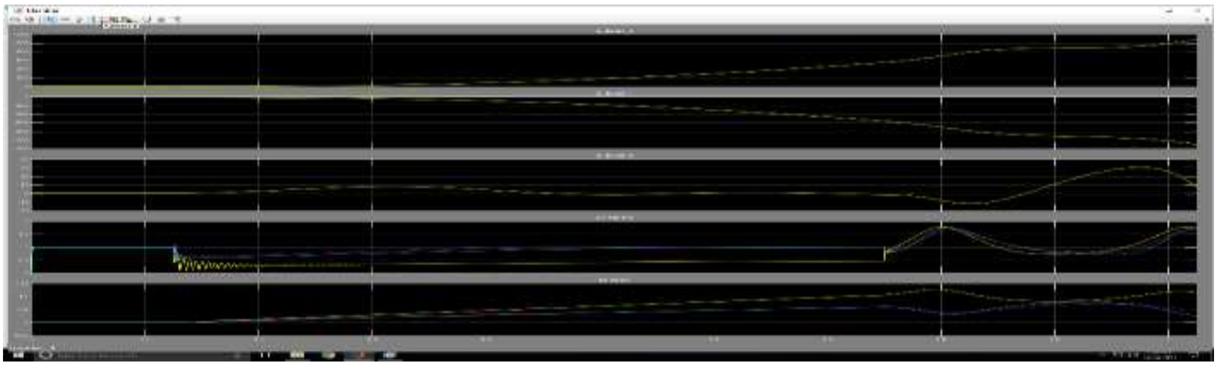

Figure11. Waveform of with three phase fault – (i) Rotor angle deviation between generator G1,G2 and G3 (ii) Speed of rotor machine G1, G2 and G3 (iii) Stator Voltage of G1, G2 and G3

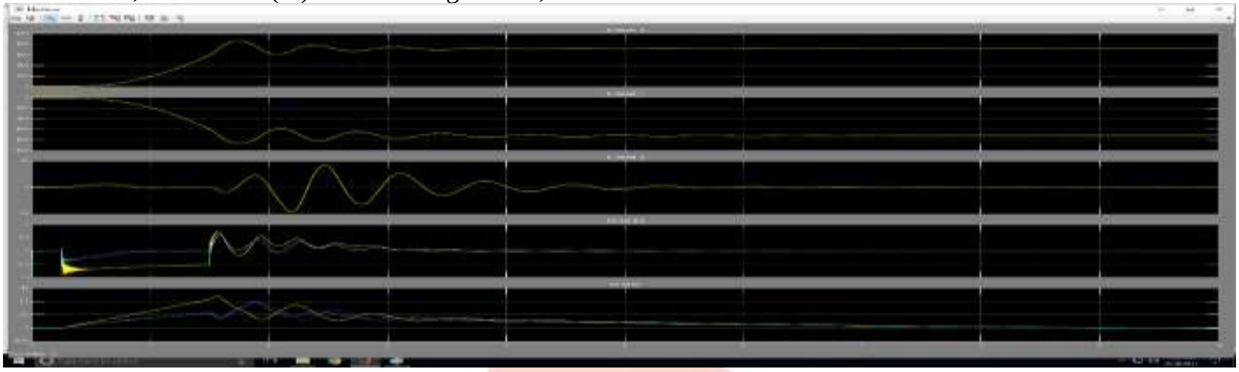

Figure12. Waveform of with three phase fault and SVC – (i) Rotor angle deviation between generator G1,G2 and G3 (ii) Speed of rotor machine G1, G2 and G3 (iii) Stator Voltage of G1, G2 and G3

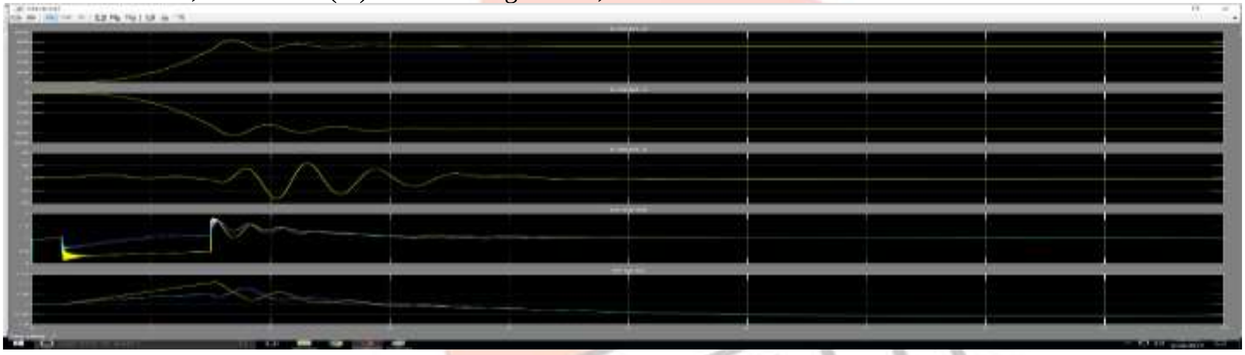

Figure13. Waveform of with three phase fault SVC&GPSS – (i) Rotor angle deviation between generator G1,G2 and G3 (ii) Speed of rotor machine G1, G2 and G3 (iii) Stator Voltage of G1, G2 and G3

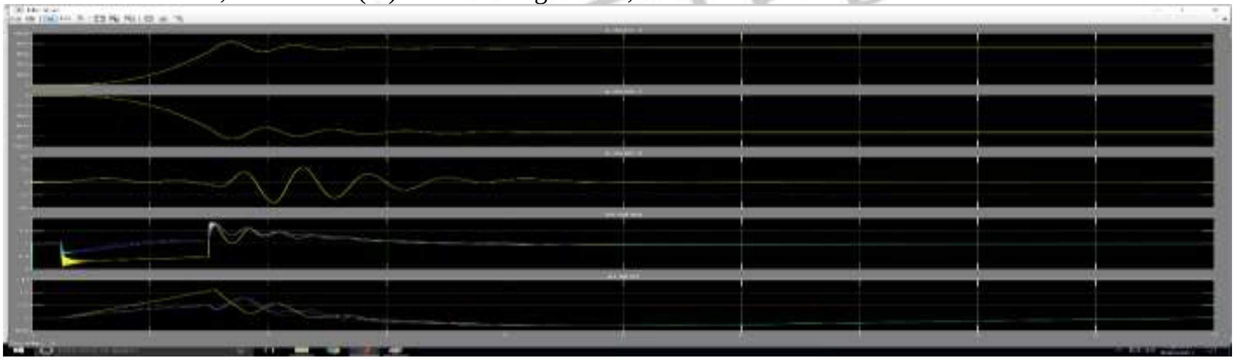

Figure14. Waveform of with three phase fault and SVC&MBPSS – (i) Rotor angle deviation between generator G1,G2 and G3 (ii) Speed of rotor machine G1, G2 and G3 (iii) Stator Voltage of G1, G2 and G3

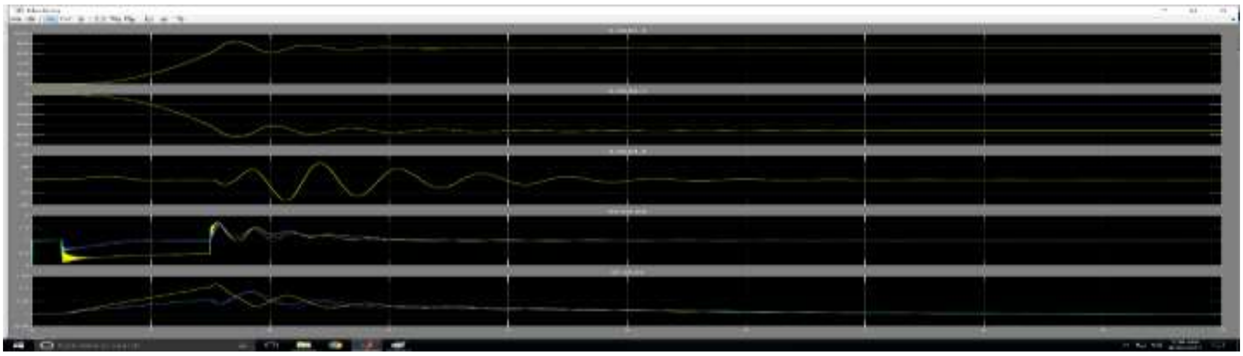

Figure15. Waveform of with three phase fault and STATCOM – (i) Rotor angle deviation between generator G1,G2 and G3 (ii) Speed of rotor machine G1, G2 and G3 (iii) Stator Voltage of G1, G2 and G3

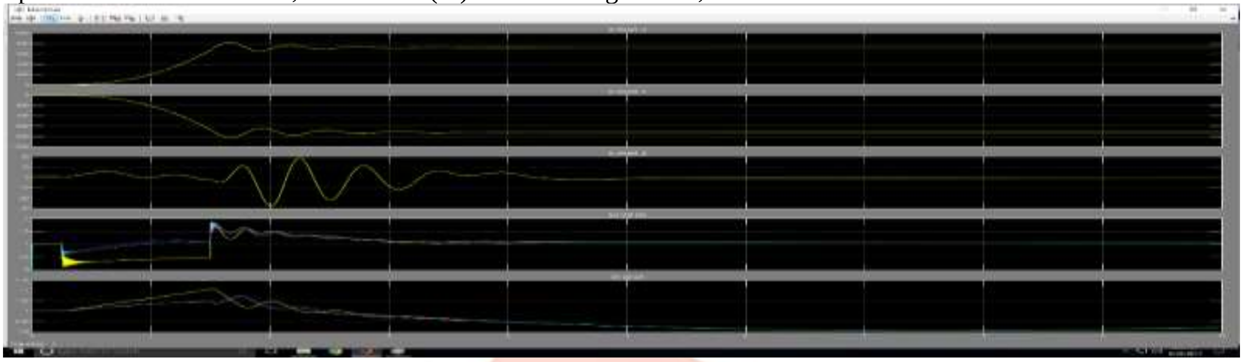

Figure16. Waveform of with three phase fault and STATCOM&GPSS – (i) Rotor angle deviation between generator G1,G2 and G3 (ii) Speed of rotor machine G1, G2 and G3 (iii) Stator Voltage of G1, G2 and G3

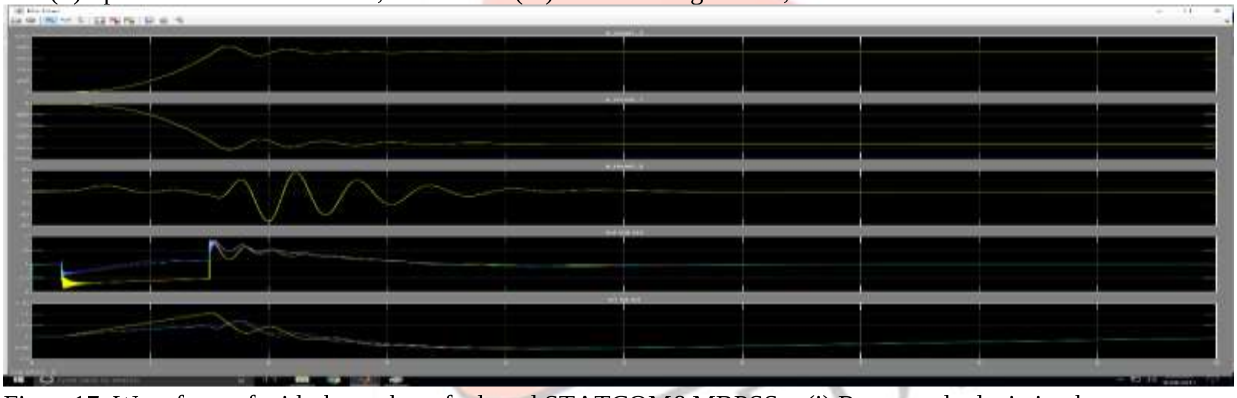

Figure17. Waveform of with three phase fault and STATCOM&MBPSS – (i) Rotor angle deviation between generator G1,G2 and G3 (ii) Speed of rotor machine G1, G2 and G3 (iii) Stator Voltage of G1, G2 and G3

6.1 Comparison between of SVC and STATCOM with and without PSS:

From simulation results shown in figure 12 to 17 comparison is made between the above facts devices with and without PSS for stability enhancement of IEEE 9 bus system as shown in table 1 and 2. From table1&2, it is clear that STATCOM with MBPSS is the effective combination for stability enhancement over SVC with MBPSS as the post fault settling time and angle deviation obtained from STATCOM with MBPSS is less as compared to that obtained from SVC with MBPSS.

Table.1 Comparison between SVC and STATCOM with and without PSS for power system stability enhancement

IEEE 9 Bus system with	Power system stability Enhancement	Stability time for d_theta 1_3 (in sec)	Stability time for d_theta 2_1 (in sec)	Stability time for d_theta 3_2(in sec)
SVC	YES	7	7.5	8.5
STATCOM	YES	5.5	6.5	7.5
SVC&GPSS	YES	4	4	5.5
STATCOM&GPSS	YES	3.5	4	5.5
SVC&MBPSS	YES	4	4	5
STATCOM&MBPSS	YES	4	4	5.3

Table.2 Comparison of angle deviation

IEEE 9 Bus system with	Angle deviation d_theta 1_3 (in deg)	Angle deviation d_theta 2_1 (in deg)	Angle deviation d_theta3_2 (in deg)
SVC	$+800^0$	-800^0	$+/-50^0$

STATCOM	$+800^0$	-800^0	$+/-25^0$
SVC&GPSS	$+800^0$	-800^0	$+/-22^0$
STATCOM&GPSS	$+800^0$	-800^0	$+/-20^0$
SVC&MBPSS	$+800^0$	-800^0	$+/-22^0$
STATCOM&MBPSS	$+800^0$	-800^0	$+/-19^0$

7. Conclusion:

(a) The dynamic behavior of the power system is compared with the presence of SVC and STATCOM in the system in the event of a major disturbance. Then the performance of STATCOM for power system stability improvement is compared with the SVC. It is clear from the simulation results (Fig. no.12&15) that there is a considerable improvement in the system performance with the use of STATCOM for which settling time in post fault is found to be around 7.5 sec. and angle deviation between generator 3 and 2 is 25^0 .

(b) The dynamic behavior of the power system is also compared with the presence of SVC with PSS and STATCOM with PSS in the system in the event of a major disturbance. Then the performance of STATCOM with MBPSS for power system stability improvement is compared with the SVC incorporated with MBPSS . It is clear from the simulation results (Fig.no.13,14,16&17) that there is a considerable improvement in the system performance with the use of STATCOM with MBPSS for which settling time in post fault is found to be around 5.3 sec. and angle deviation between generator 3 and 2 is 19^0 . The SVC with MBPSS also gives effective result for which settling time is found to be 5 sec, but the angle deviation with this combination is 22^0

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