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Research Article

A Comparative Study of Performances of PSS and SVC for Rotor Angle Stability Enhancement in 3 Bus 2 Generator System

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Abstract: This study deals with the comparative analysis of performances of power system stabilizer and SVC. A 3 bus 2 generator power system network is used as a test system. Both generic PSS and multi band PSS are first analyzed. The fault analysis is carried out for the above test system with both generic and multi band PSS. It is observed that multi-band PSS resulted in better transient response for single phase faults. The multi band PSS resulted in good dynamic response due to absence of low frequency oscillations after clearing the fault. The system became unstable for three phase fault in both types of PSS. Then the SVC is connected in the above test system. The fault analysis is carried out with SVC connected at the midpoint of the above system. The simulation results show that performance of SVC for voltage and rotor angle stability is improved compared to multi-band PSS based system and also the system could regain its stability after removing three phase fault. It is also observed that SVC improves transient stability margin by increasing the critical clearing time and reducing rotor angle oscillations. The simulation is carried out using MATLAB software.

Keywords: Electromechanical oscillations, fault analysis, generic, multi band, power system stabilizer, rotor oscillations, static VAr compensator

INTRODUCTION

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 (Bourles *et al*., 1998; Kundur *et al*., 1989; Taylor, 1993). Electromechanical oscillations can be classified in four main categories.

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 4.0 Hz.

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

Inter area oscillations: Between two major groups of generation plants. Frequencies are typically in a range of 0.2 to 0.8 Hz.

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 0.2 Hz (Fig. 1).

The large interconnected power transmission systems results in all the four electromechanical oscillations. These Oscillations results in outage which can be overcome either by using Power System Stabilizers (PSS) and Flexible AC Transmission Systems (FACTS) controllers (Padiyar, 1996; Anderson and Fouad, 2003). Conventionally the generic power system stabilizers were used damp these oscillations and to prevent outages (Kundur, 1999; Huerta *et al*., 2010). The response of generic PSS was found to be slow which led to a new concept of multi band PSS. It is observed that multi band PSS is very effective and fast in damping the all four modes of oscillations compared to generic type PSS. As the power system complexity increased due to denser interconnections the multi band PSS failed to damp the oscillations for three phase fault. This can be overcome by using FACTS controllers. There are many FACTS devices that are used to damp the oscillations and mitigate voltage sag in interconnected power systems. In this study, SVC is connected at the midpoint of two bus system with multi band PSS to damp the oscillations and to prevent outage during fault conditions (Padiyar, 1996).

To validate the results a simple 3 bus 2 generator system is used (Kundur, 1999; Murdoch *et al*., 1999; Grondin *et al*., 1993). Initially a generic PSS is implemented in the above system and the simulation

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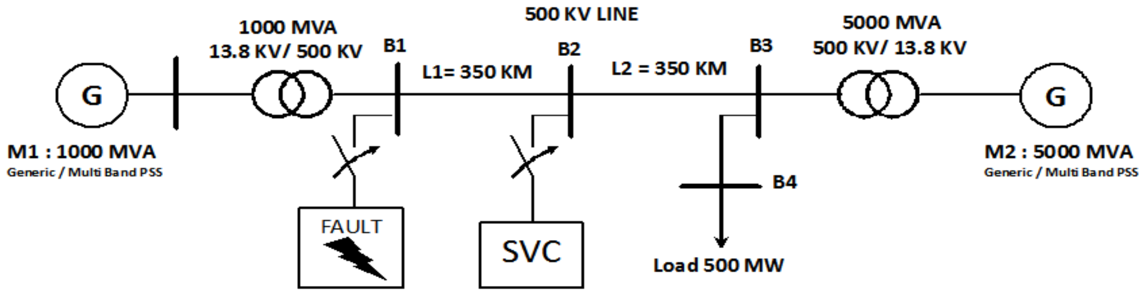

Fig. 1: Single line diagram of 3 bus 2 generator system

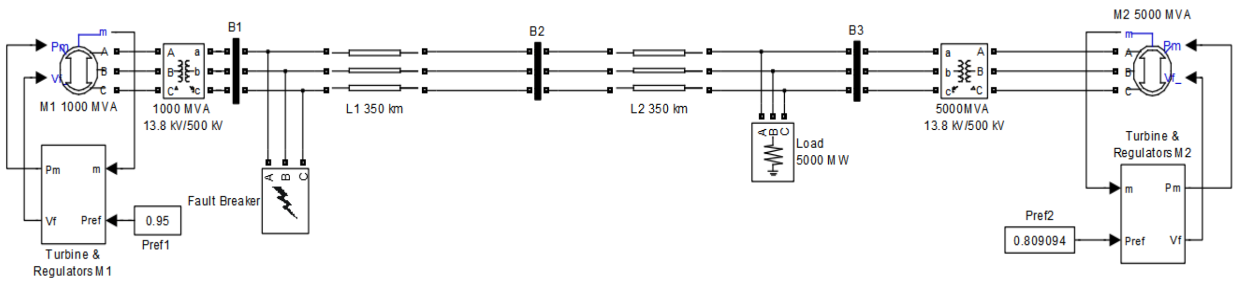

Fig. 2: MATLAB simulation of 3 bus 2 generator system

results are observed. The fault analysis is done by applying fault at bus B1. The system is subjected to different fault conditions like single line to ground fault, double line to ground fault and three phase fault and the system stability is observed. From the results it is observed that both the generic and multi band PSS are capable of withstanding the single and double phase fault but unable to withstand the three phase fault. The generic PSS resulted in low frequency oscillations after clearing the single phase fault. Whereas the multiband PSS damped the low frequency oscillations after clearing single phase fault and restored the system to normal state without any oscillations. The system is then tested with SVC FACTS controller at midpoint of transmission system, which can supply or absorb the reactive power with respect to the firing instant of parallel connected SCR's. The closed loop control of SVC is implemented using PI controller which maintains the voltage at the bus connected by smooth variation in firing angle (Messina *et al*., 2003). The variation in firing angle results in change in reactive power supplied or absorbed to the system and thus results in voltage stability. When subjected to three phase fault with SVC connected to midpoint of transmission system, system could restore the normal state when the fault is cleared. Thus the SVC connected at midpoint improves the system stability by preventing outages for three phase faults.

This study is organized as follows. First the 3 bus 2 generator systems is implemented with generic PSS and then the results are compared with implementation of multiband PSS. Then the system is analyzed using SVC device to overcome faults. This study focuses on comparative performance analysis of types of PSS and SVC controllers in mitigating the voltage sag and faults in interconnected power systems. From this study it is clear that SVC improves system dynamic response and stability by increasing the critical clearing time for fault clearance and reduces percentage voltage sag.

METHODOLOGY

Description of 3 bus 2 generator test system: The test system consists of 2 machines connected with 3 buses (Kundur, 1999; Murdoch *et al*., 1999; Grondin *et al*., 1993). Plant 1 (M1) is a 1000 MW hydraulic generation plant connected to a load centre through a 700 km long 500 KV transmission line. The load centre is represented as a 5000 MW resistive load and supplied by the remote plant 1 (M1) consisting of a 1000 MVA plant and a local generation of 5000 MVA. The test system in MATLAB is shown in Fig. 2.

A load flow has been performed on this system with M1 generating 950 MW and M2 generating 4046 MW. The line carries 944 MW which is close to its surge impedance loading (SIL = 977 MW). The two

Table 1: Parameters specified for 3 bus 2 generator test system in load flow analysis

Machine number	Parameters	Values
Machine M1	Type	PV bus
	PV terminal voltage	13800 V_{rms}
	Active power	950 MW
Machine M2	Type	Swing bus
	PV terminal voltage	13800 V_{rms}
	Active power guess	4000 MW

Table 2: Load flow results for 3 bus 2 generator test system

Parameter	Real power (MW)	Reactive power (Mvar)
Total generation:	P = 4995.47	Q = 406.12
Total Z_shunt load:	P = 4941.25	Q = -925.46
Total losses:	P = 54.22	Q = 1331.58
Bus 1- V = 1.000 pu/13.8 kV 0.00 deg; Swing bus		
Generation:	P = 4045.47	Q = 385.76
Z_shunt:	P = 10.16	Q = 9.83
Bus 1 to 2	P = 4035.31	Q = 375.93
Bus 2- V = 0.992 pu/500 kV 24.42 deg		
Z_shunt:	P = 4926.75	Q = -464.78
Bus 2 to 1	P = -4022.17	Q = 18.27
Bus 2 to 4	P = -904.58	Q = 446.51
Bus 3- V = 1.000 pu/13.8 kV 49.34 deg; PV bus		
Generation:	P = 950.00	Q = 20.36
Z_shunt:	P = 2.03	Q = 1.97
Bus 3 to 4	P = 947.97	Q = 18.40
Bus 4- V = 1.000 pu/500 kV 72.81 deg		
Z_shunt:	P = 2.31	Q = -472.47
Bus 4 to 2	P = 942.06	Q = 382.99
Bus 4 to 3	P = -944.37	Q = 89.48

machines are equipped with a Hydraulic Turbine and Governor (HTG), excitation system and Power System Stabilizer (PSS). The parameters specified in MATLAB are tabulated in Table 1. The results of load flow are tabulated in Table 2.

The Power System Stabilizer (PSS) is a control device which provides maximum power transfer and optimal power system stability (Gibbard and Vowels, 2004; Abdel-Magic *et al*., 2000; Bourles *et al*., 1998). PSS has been widely used to damp electromechanical oscillations that occur in power systems due to disturbances. If no adequate damping is available, the oscillation will result in instability (Abdel-Magic *et al*., 2000; Ali and Mansour 2004; Grondin *et al*., 2003). The PSS are of two types in common: Generic and Multiband PSS. A generic model uses the acceleration power (P_a = difference between mechanical power P_m and output electrical power P_{eo}) and a Multi-band stabilizer uses the speed deviation (dw). First, the generic type PSS is implemented in generation system and the fault analysis is carried out. Then the Multi-band PSS is implemented in generation system and the fault analysis is performed. From the simulation results it is observed that multi band PSS damps the low frequency oscillations after clearing the fault (Prasertwong *et al*., 2010). Both the generic PSS and Multi band PSS could not regain the system stability for three phases fault. But when the SVC is implemented in the midpoint of the transmission line, the system regains its stability after clearing the fault. The simulation is performed using MATLAB software and results are presented for different types of fault with generic and Multi band PSS. Then the improvement of system response with SVC installed at midpoint of transmission line is also presented.

The load flow on 3 bus 2 generator system is performed after initializing the synchronous machines and regulators (Esquivel *et al*., 2000; Kundur, 1999). The machine M1 is initialized as PV generator to control the active power generated and its terminal voltage. The machine M2 is initialized as swing bus.

Modelling of SVC: Only for detailed study of SVC control interactions, a detailed SVC model including switching of thyristor valves in TCR and TSC is necessary. But for stability studies it is not necessary to consider the switching of valves. It is sufficient to assume that SVC generates only fundamental current (Cong *et al*., 2004; Esquivel *et al*., 2000; Perez *et al*., 2000). The harmonics are neglected and are represented by algebraic equation given in (1). Y, V and I are admittance, voltage and current matrices:

$$[Y][V] = [I] \tag{1}$$

Thus the SVC is modelled as variable suceptance which is the output of the control system shown in Fig. 3. Thus for stability studies, the dynamics of SVC control is ignored and the SVC is described by the steady state control characteristics (Wang *et al*., 2000).

Steady state model of SVC: The steady state control characteristics are modelled by equivalent circuit shown in Fig. 4. The voltage source E_{svc} is in series with a reactor X_{SVC}. The values of E_{svc} and X_{SVC} are given below for three operating regions:

- Control range
- Capacitive limit
- Inductive limit as discussed below (Padiyar, 1996; Li *et al*., 2010)

The V_{ref} is the reference voltage input to the SVC.

Control range:

$$E_{svc} = V_{ref}\angle\emptyset_{svc} \tag{2}$$

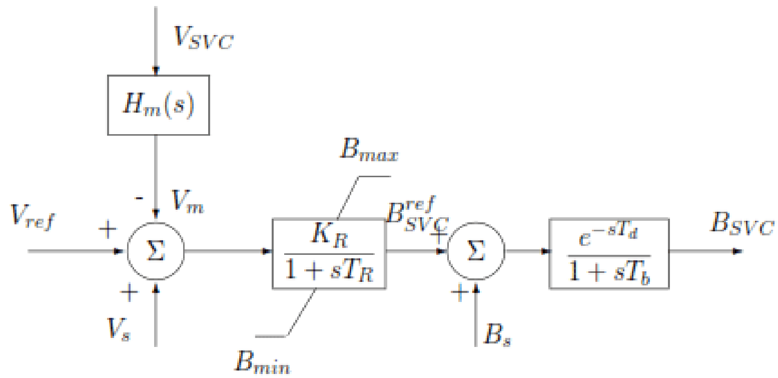

Fig. 3: SVC block diagram for voltage control

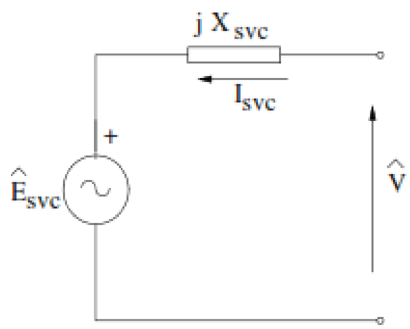

Fig. 4: SVC equivalent circuit

$$X_{svc} = X_s \tag{3}$$

where, Φ_{svc} is the angle of SVC bus voltage. The control range applies when the SVC bus voltage is in the range:

$$\frac{V_{ref}}{1+X_s B_{max}} < V_{svc} < \frac{V_{ref}}{1+X_s B_{min}} \tag{4}$$

where, B_{max} and B_{min} are the limits of B_{svc}. B_{min} corresponds to inductive limit and Bmax corresponds to capacitive limit (i.e.,) $B_{max}= B_c$, where B_c is the total capacitive suceptance.

At capacitive limit:

$$E_{svc} = 0.0 + j0.0 \tag{5}$$

$$X_{svc} = \frac{1}{B_{max}} \tag{6}$$

At inductive limit:

$$E_{svc} = 0.0 + j0.0 \tag{7}$$

$$X_{svc} = \frac{1}{B_{min}} \tag{8}$$

The network external to SVC is modelled as thevenins equivalent circuit (Modi *et al*., 2010, 2011). Zeq is the impedance of the network as seen at the SVC terminals when all the sources in the network are removed (the voltage sources are shorted and current sources are open circuited). Veq is found as SVC terminal voltage with SVC current zero. From Fig. 5, the SVC current is computed as:

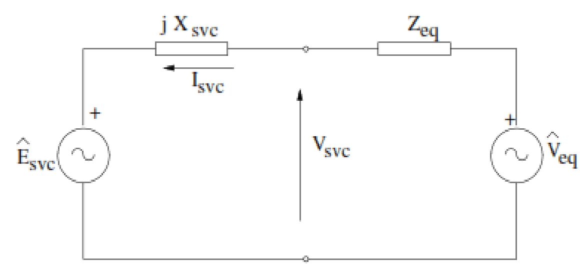

Fig. 5: SVC connected to thevenin equivalent circuit

$$I_{svc} = \frac{V_{eq} - E_{svc}}{Z_{eq} + j\, X_{svc}} \tag{9}$$

Analysis of SVC connected to mid point: The location of SVC is important in determining its performance and effectiveness. Ideally, it should be located at the electrical centre of the system or mid point of the transmission line (Zhao and Jiang, 1995; Rahim and Nassimi, 1996). In Fig. 5 the SVC is connected at the midpoint. Without SVC, the mid point voltage is given by:

$$Vm = \frac{V\cos(\frac{\delta}{2})}{\cos(\frac{\theta}{2})} \tag{10}$$

where, $\Theta = \beta\ l$ is the electrical length of the line. Where, l is the length of the line and β is the phase constant. Given by $\beta = \omega\sqrt{lc} = 2\pi f\sqrt{lc}$ where l and c are the positive sequence inductance and capacitance of the line per unit length and f is the operating frequency.

From the Eq. (10) it can be shown that the voltage variation of the line due to variation of δ is maximum at the midpoint. SVC helps to limit the variation by suitable control. The steady state characteristics of SVC

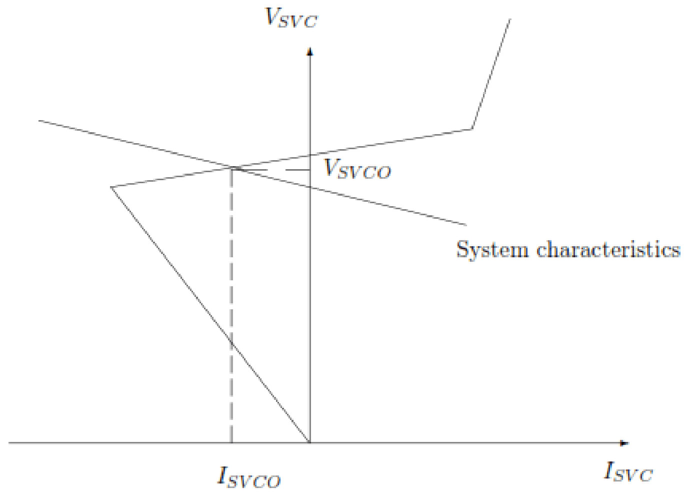

Fig. 6: SVC control characteristics

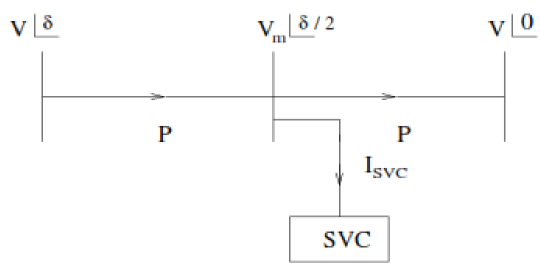

Fig. 7: SVC connected in the midpoint of the transmission line

are shown in the Fig. 6. Here ADB is the control range. OA represents the characteristic where SVC hits the capacitive limits. BC represents the SVC at its inductor limits. Thus $I_{SVC} = - B_{SVC}. V_{SVC}$.

A positive slope is given to control range to prevent SVC hitting the limits frequently. The steady state value of SVC bus voltage is determined from the intersection of system characteristic and the control characteristic as shown in Fig. 6. The system characteristic is a straight line with negative slope and is defined by:

$$V_{SVC} = V_{th} - X_{th}.I_{SVC} \tag{11}$$

where, V^{th} and X^{th} are the thevenins voltage and reactance viewed from SVC bus. For the system shown in the Fig. 7:

$$V_{th} = V_{mo} = \frac{V\cos\left(\frac{\delta}{2}\right)}{\cos\left(\frac{\theta}{2}\right)} \tag{12}$$

$$X_{th} = \frac{Z_n}{2}\tan\left(\frac{\theta}{2}\right) \tag{13}$$

where, $Zn = \sqrt{\frac{l}{c}}$ Zn = surge impedance.

Expression for voltage and power in control range: The SVC control range is given by:

$$V_{SVC} = V_{ref} + X_s.I_{SVC} \tag{14}$$

where, X_s is the slope of the control characteristic. V_{ref} is the SVC voltage when $I_{SVC} = 0$. From Eq. (11) and (14) we get voltage injected by SVC and power flow in line due to SVC as follows (Taylor, 2000):

$$V_{SVC} = V_m = \frac{V_{th}X_s}{X_s+X_{th}} + \frac{V_{ref}X_{th}}{X_s+X_{th}} \tag{15}$$

$$P = \frac{V_m V\sin(\frac{\delta}{2})}{Z_n\sin(\frac{\theta}{2})} \tag{16}$$

POWER ANGLE CURVE WITH SVC

The power as the function of δ is shown in Fig. 8. The power angle curve of line without SVC is also shown in Fig. 8 as curve b.

Modelling of generic PSS: 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 (Bourles *et al*., 1998). 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 to the Excitation System block (Murdoch *et al*., 1999). The PSS input signal can be either the machine speed deviation, dw, or its acceleration power, Pa = Pm - Peo that is difference between electrical and mechanical power.

The Generic Power System Stabilizer is modelled by the following nonlinear system as shown in Fig. 9.

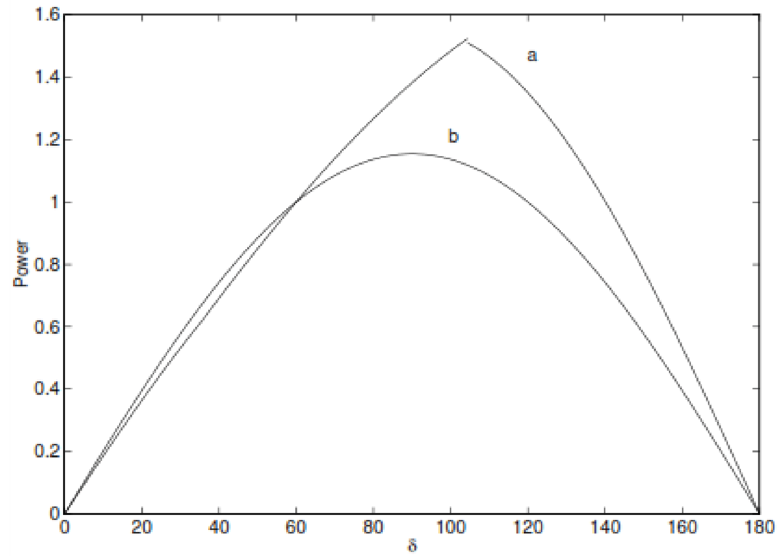

Fig. 8: Power angle curve with and without SVC

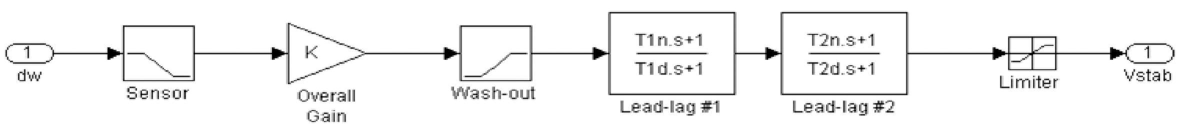

Fig. 9: Generic power system stabilizer model

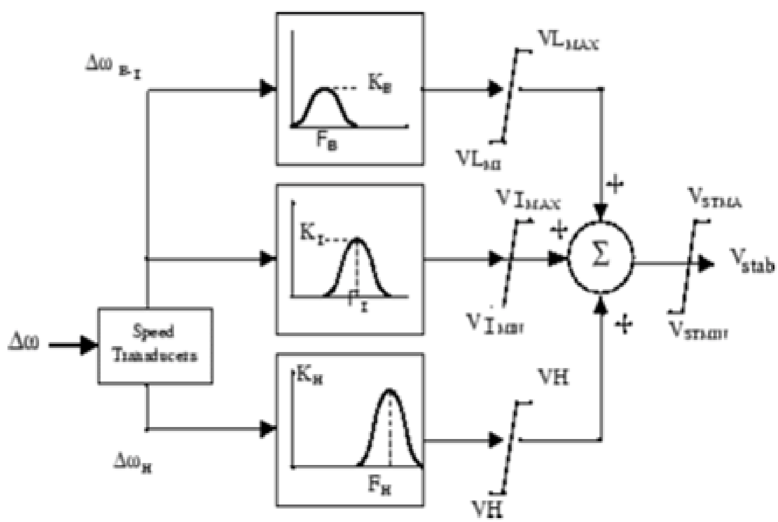

Fig. 10: Multi band power system stabilizer model

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 (Murdoch *et al*., 1999). 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.

Modelling of multi band PSS: The multi band PSS gets a phase advance at all frequencies of rotor oscillations to compensate for the inherent lag between field excitation and electrical torque (Murdoch *et al*., 1999). The performance of damping of rotor oscillations is more effective in multiband PSS by controlling the excitation current during disturbances. The MB PSS is very fast during transient disturbances and restores the system stability quickly.

The MB PSS structure is based on multiple working bands. It has three separate bands respectively used for low, intermediate and high frequency modes of oscillations (Ramirez *et al*., 2009; Wang *et al*., 2009). The low band is associated with power system global mode, intermediate band with inter area modes and high band with local modes. Each three band is made of differential band pass filter, gain and limiter as shown in Fig. 10. The outputs of the three bands is summed and then passed through final limiter producing the stabilizer output V_{stab}. Thus this improves the damping of electromechanical oscillations.

SIMULATION OF TEST SYSTEM WITH PSS AND SVC

In the test system, a fault breaker has been inserted nearer to the Bus 1. The fault is generated at 5^{th} sec and it's cleared by 0.1 sec. Seven parameters namely, Midpoint voltage, SVC susceptance, Bus voltages (V1, V2, V3), line power, terminal voltage, speed of G1 and G2, rotor angle of the system are observed for the study.

After clearing the fault, if the system takes long time to reach stable condition, it will lose its synchronism. In order to avoid this, a Power System Stabilizer (PSS) is connected to the system. In order to maintain system stability after faults, the transmission line is shunt compensated at its centre by a 200-Mvar Static Var Compensator (SVC). The results obtained from the system connecting with Generic and Multiband PSS are shown individually. Then the fault analysis is carried out with generic and multi band PSS separately. The SVC is then connected to midpoint of transmission line and the fault analysis is carried out.

Transient stability analysis of 3 bus 2 generator systems: Electric Power system is growing in size and complexity in all sections such as generators, transmission and distribution and load systems. The faults in the power system results in severe economic losses due to loss of synchronism between the generators of different areas. The causes of faults are due to lightning strikes, heavy winds, equipment failures, insulation breakdown, etc. The faults results in power swings, loss of synchronism between the machines, interruption of supply and thus effects the reliability of the power system. The above test system is subjected to following types of faults with various devices like generic PSS, Multiband PSS and then SVC. The system stability of the 3 bus 2 generator system is studied for the following cases.

Case 1: Single phase fault at Bus B1, without PSS at generators.
Case 2: Single Phase fault with GPSS installed at generators.
Case 3: Single phase fault with MPSS installed at generators.
Case 4: Double line fault results comparisons of GPSS and MPSS at generators.
Case 5: Three fault results comparisons of GPSS and MPSS at generators.
Case 6: Three phase fault with SVC connected at midpoint of the transmission line.

Case 1: Single phase fault at bus B1, without PSS at generators: The test system is simulated disconnecting both PSS and SVC. A single phase fault is applied at bus B1 at 5^{th} second for duration of 0.1 Sec. The results are as shown in Fig. 11. From the Fig. 11 it is observed that the system goes out of synchronism when the fault is cleared at 5.1 sec. From the Fig. 11 it is observed that suceptance (B) is zero and therefore SVC is not connected to the system. The rotor angle theta, bus voltage and the speed of machines M1 and M2 collapses. The system therefore fails to regain its stability due to loss of synchronism between the two machines M1 and M2. Thus with both PSS and SVC not connected, the system loses its synchronism and becomes unstable for single phase fault duration of 0.1 sec at bus B1. This can be overcome by installing PSS in both machines M1 and M2.

Case 2: Single phase fault with GPSS installed at generators: The test system is simulated using generic PSS in both machines M1 and M2. The SVC is used in fixed suceptance mode with B_{ref} = 0, which is equivalent to putting SVC out of service. The single phase fault is applied at 5^{th} sec for duration of 0.1 sec at bus B1. The results are as shown in Fig. 12. From the Fig. 12, it is observed that after fault clearing, the system remains stable. The machines M1 and M2 remains in synchronism after fault clearing. But the speed of the machines M1 and M2 oscillates together at a low frequency of 0.025 Hz after fault clearing. Thus the generic PSS succeeds in regaining system stability, but not efficient to damp the 0.025 Hz oscillations in speed of both machines. This problem can be overcome by using multi band PSS in both machines M1 and M2.

Case 3: Single phase fault with MPSS installed at generators: Now Multiband PSS is used in both machines M1 and M2. As in the previous case, the SVC is put out of service by making B_{ref} = 0. The single phase fault is applied at 5^{th} sec for 0.1 sec duration at bus B1. The results are shown in figure.

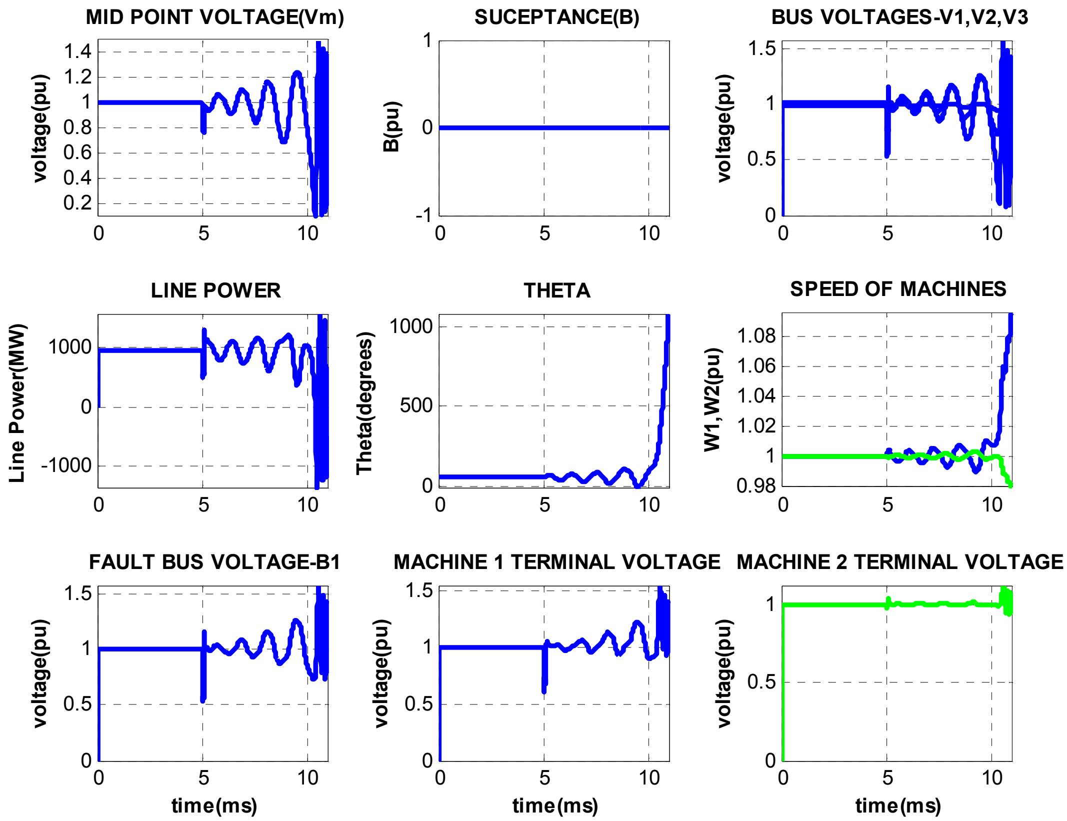

Fig. 11: Output waveforms for single phase fault no PSS at generator and SVC not connected

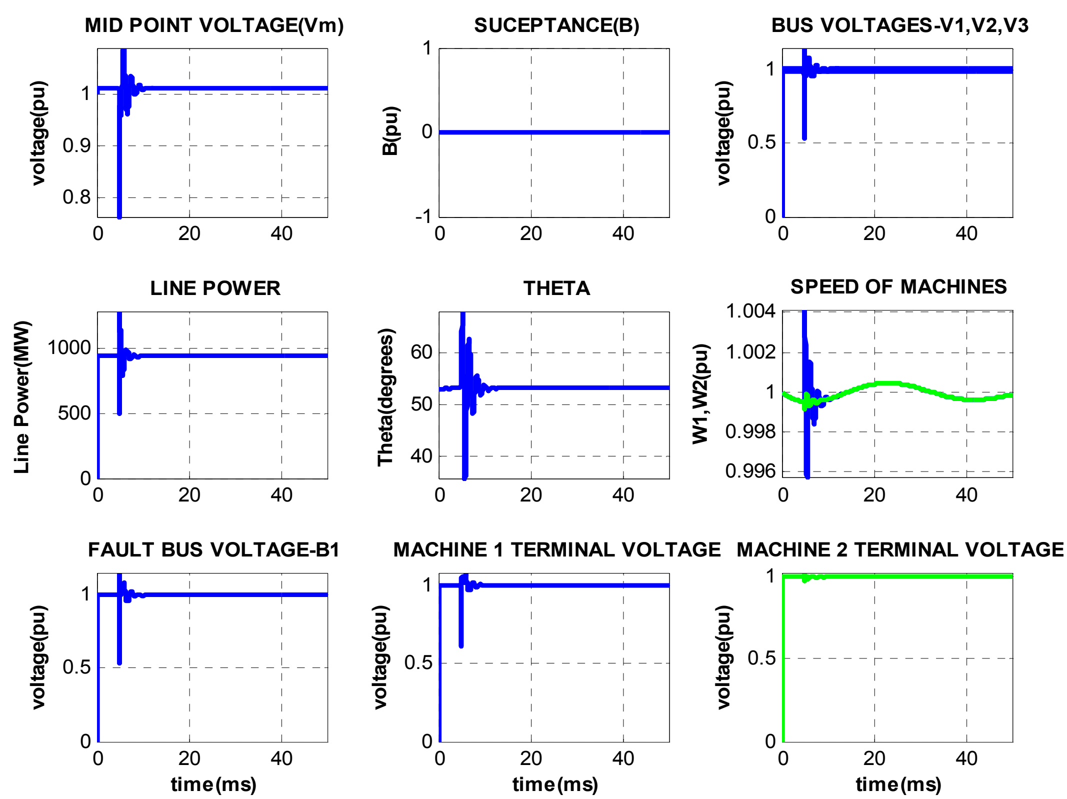

Fig. 12: Output waveforms for single phase fault with GPSS

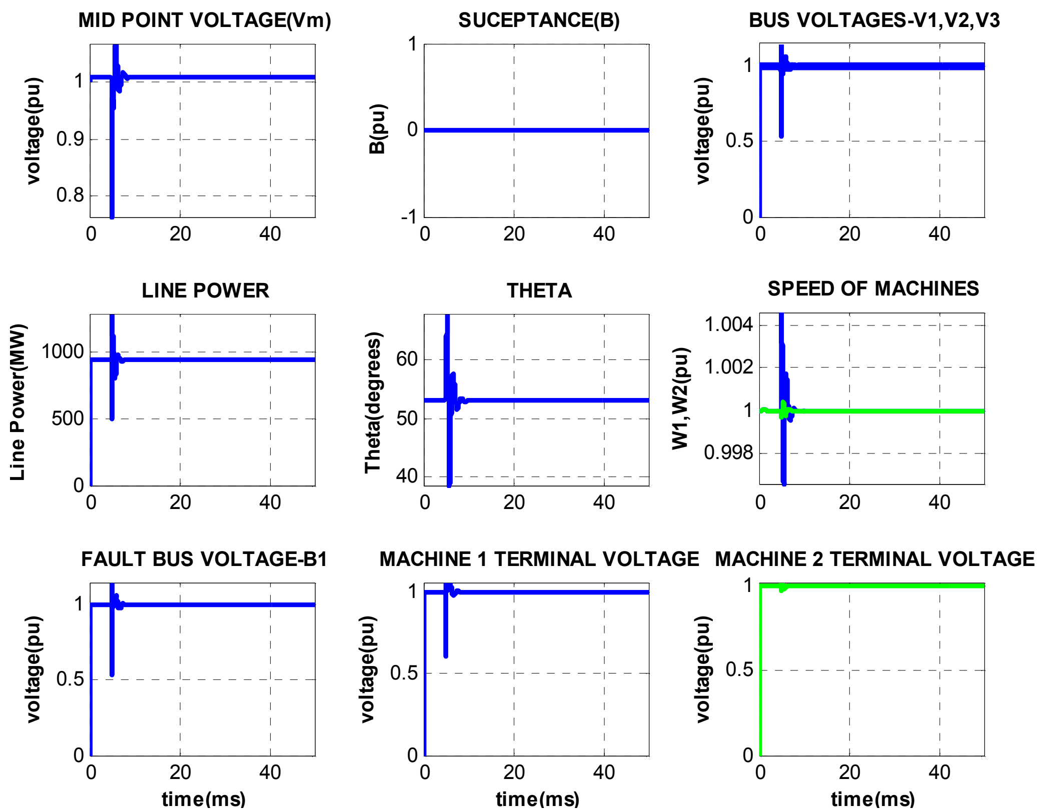

Fig. 13: Output waveforms for single phase fault with MPSS

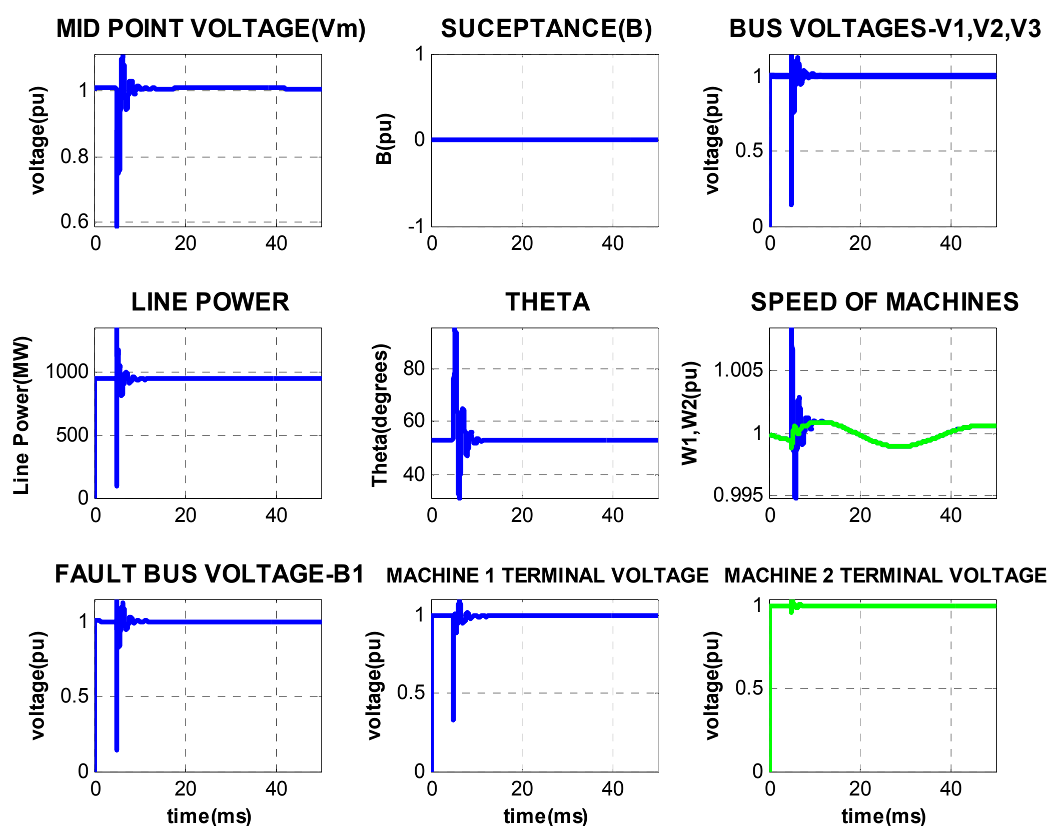

Fig. 14: Output waveforms for double line fault with GPSS

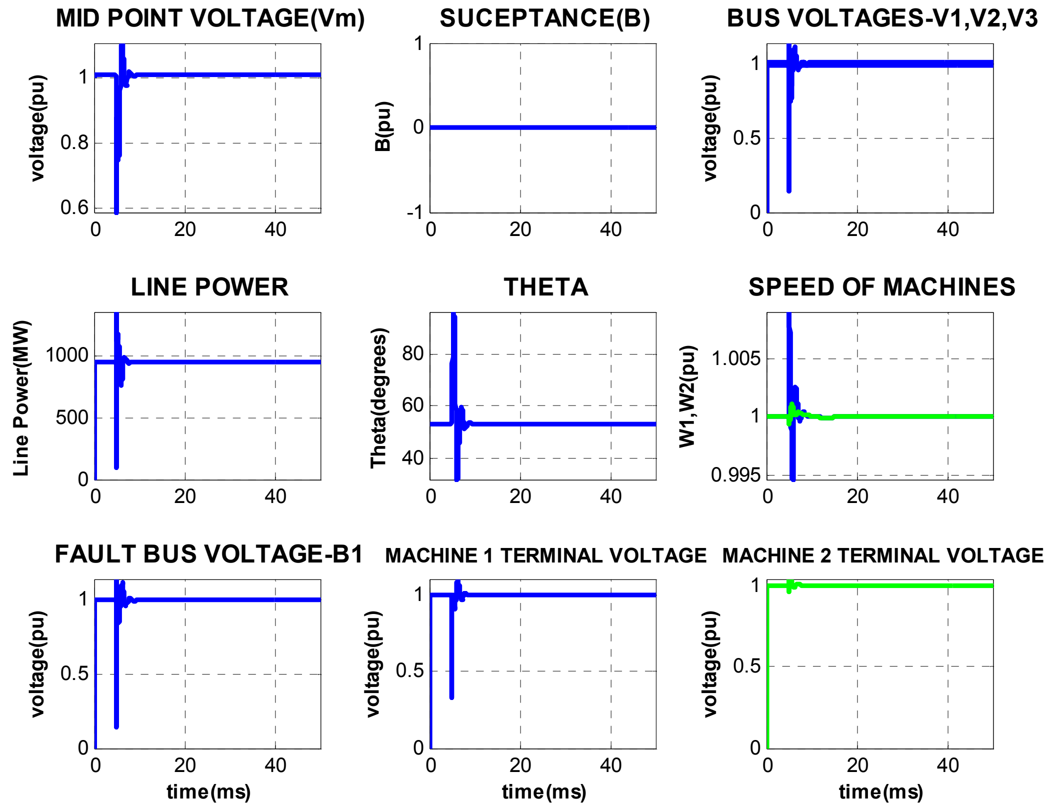

Fig. 15: Output waveforms for double line fault with MPSS

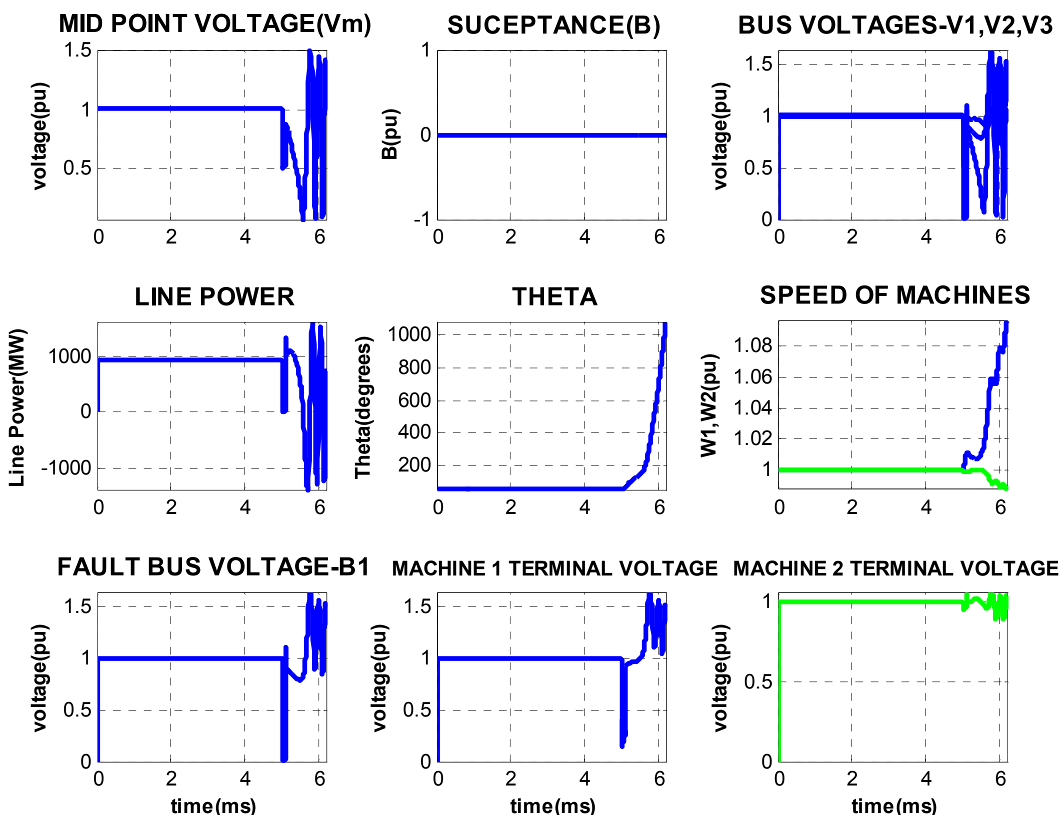

Fig. 16: Output waveforms for three phase fault with GPSS

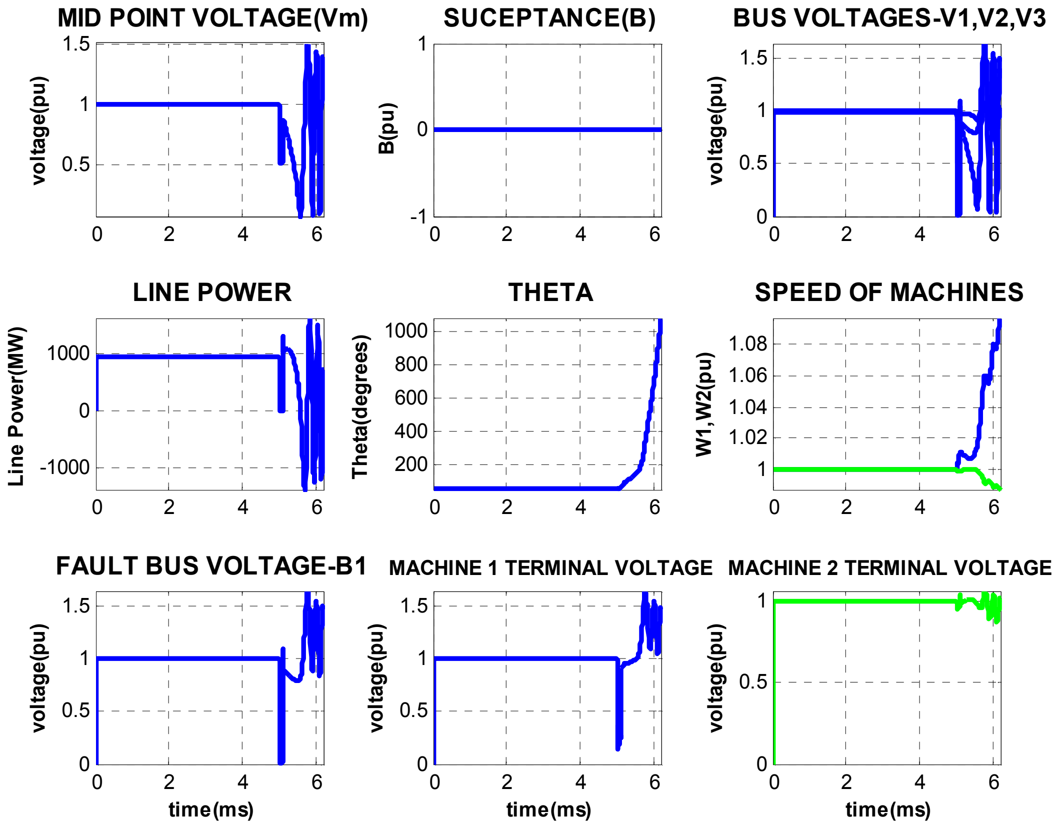

Fig. 17: Output waveforms for three phase fault with MPSS

From the Fig. 13, it is observed that after fault clearing the system regains stability. It is also observed that 0.025 Hz mode of oscillation in speed of machines M1, M2 waveform is absent, which was present when using generic PSS. Thus the multi band PSS succeeds in damping 0.025 Hz mode of oscillation quickly therefore the system regains stability at faster rate compared to generic PSS. Thus Multi band PSS is found to have superior functionality in regaining stability compared to generic PSS for single phase faults.

Case 4: Double line fault results comparisons of GPSS and MPSS at generators: When subjected to double line fault, both generic and multi-band PSS are able to regain the system stability. The waveforms are as shown in the Fig. 14 and 15. From the waveforms it is observed that the system response is similar to single phase fault. The generic PSS based system fails to damp 0.025 Hz oscillation mode in speed of machines M1 and M2, whereas multi band PSS based system succeeds in damping 0.025 Hz oscillations.

Case 5: Three fault results comparisons of GPSS and MPSS at generators: The three phase fault is applied at bus B1 at 5^{th} sec for 0.1 sec duration. The results for both generic and multi band PSS is shown in Fig. 16 and 17. It is observed from the Fig. 16 and 17 that both generic and multi band PSS are unable to restore system stability. The rotor angle theta, bus voltages and the speed of machines M1, M2 collapses. The synchronism between the machines is lost. Thus the system is unable to recover from the three phase fault even after fault clearing. This problem can be overcome by using SVC at midpoint which is proved in the next section.

Case 6: Three phase fault with SVC connected at midpoint of the transmission line: The three phase fault resulted in severe contingency for both generic and multi band based PSS installed in machines M1, M2. It resulted in loss of synchronism between the machines M1, M2 after clearing three phase fault of duration 0.1 sec. Now SVC is connected to Bus B2 to regulate the voltage as shown in Fig. 18. The SVC regulates the voltage by injecting reactive power in the line when the voltage is lower than the reference voltage that is 1 p.u., During normal steady state the SVC will be in floating state. When the voltage starts reducing below reference value, the SVC maintains the voltage by compensating it with reactive power. From the Fig. 19, it is observed that SVC can restore the system to normal steady state after fault clearing for any type of fault. The rotor angle stability curve with and without SVC connected is as shown in Fig. 20.

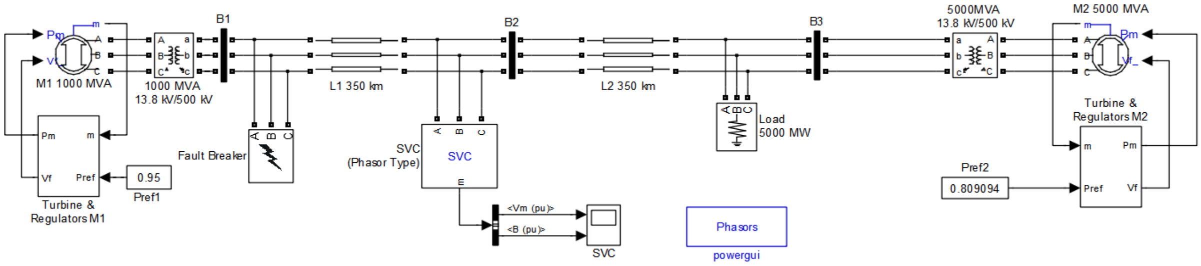

Fig. 18: Test system with SVC at midpoint of transmission line

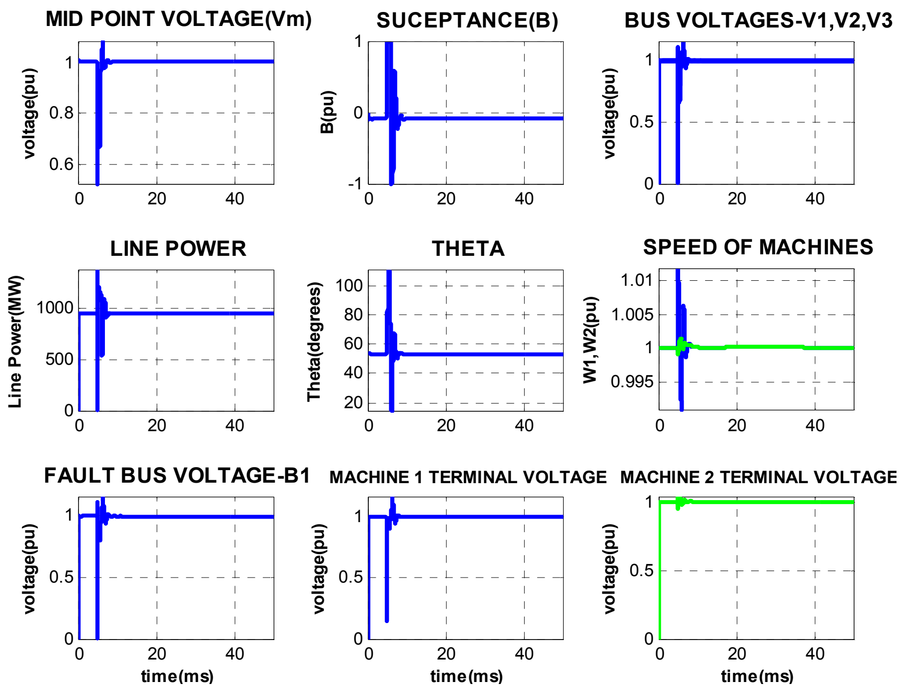

Fig. 19: Output waveforms for three phase fault with SVC at mid point

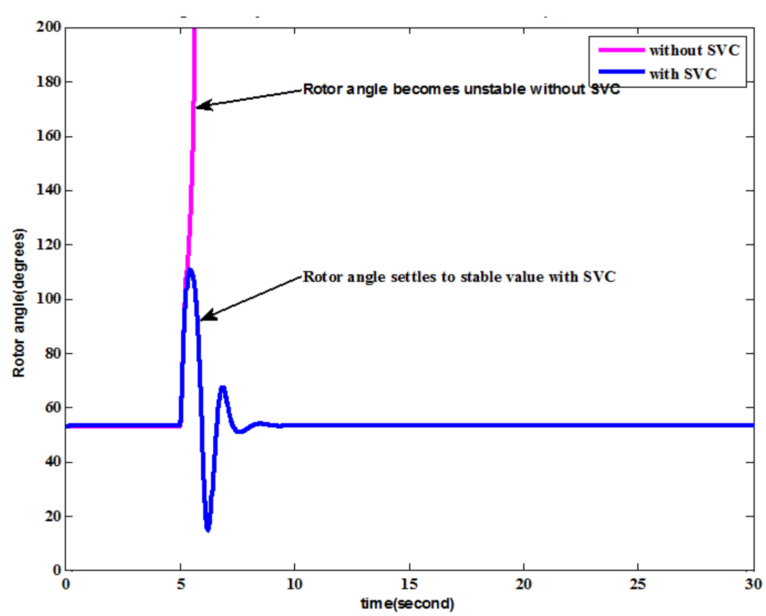

Fig. 20: Rotor angle stability curve with and without SVC

Therefore the system stability is restored when SVC is used to inject reactive power for voltage regulation. Thus the SVC can restore the system stability even during severe contingency like three phase fault at BUS B1.

CONCLUSION

In this study, the transient stability analysis of 2 machine system incorporating generic and multi band PSS is first studied. From the results it is studied that both generic and multi band PSS could restore system stability for simple single and double line faults. It is observed that multi band PSS could damp the low frequency oscillations after fault clearing whereas generic PSS fails to damp low frequency oscillations after fault clearing. But both PSS could not establish system stability for three phase faults. After SVC installation at midpoint of transmission line, the results proved that system regains stability after fault clearing for any type of fault. Thus the SVC improves the transient stability margin of power system network, irrespective of any type of fault. From this study, the impact of PSS and SVC for transient stability enhancement is studied. Simulation results show that, security level of power system network can be enhanced by installing SVC at midpoint of transmission line.

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