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Design and Simulation of Robust Damping Controllers for Small-Signal Stability Enhancement Using PSS and STATCOM in a Multi-Machine System

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ABSTRACT

In a power system where the traditional synchronous generators are used for power generation, uncertainty exists because of small, continuous perturbations, such as minor load fluctuations, and insufficient damping which can lead to low frequency oscillation. To maintain the power system stability which involves damping of the low frequency oscillations, we can introduce Robust Damping Controllers using a combination of PSS and STATCOM. This paper presents the Design and Simulation of Robust Damping Controllers for Small-Signal Stability Enhancement Using PSS and STATCOM in a Multi-Machine System. This was achieved by modelling a 9-bus power system which is the Multi-Machine System, modelling a STATCOM, also modelling a PSS using MATLAB Simulink and finally simulating the entire system after the STATCOM and the PSS models were incorporated into the Multi-Machine System. The outcome of the analysis reveals that the design combination of the STATCOM and the PSS has an exceptional capability in damping a power system's low frequency oscillations, and it also greatly improves the dynamic stability of power systems.

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INTRODUCTION

There is a massive rate of growth in today's world, and because of such growth rate there is also the need for proportional growth in the generation, transmission and distribution of electrical power systems to meet the demand and requirements of the growth. The stability of the power system is also key to meeting the demand and requirements of the massive growth rate.

Power system stability may be broadly defined as the property of a power system that enables it to remain in a state of operating in equilibrium under normal operating condition and to regain an acceptable state of equilibrium after being subjected to a disturbance [1]. The stability of this system needs to be maintained even when subjected to disturbance that is large and has a slim chance of occurring so that there will be a secure and reliable supply of electricity to the consumers.

In large-interconnected power systems, the variation in load and generation causes the rotors of synchronous machines to swing, causing changes in machine rotor angles, terminal voltages, and frequencies that affect the power system equilibrium. Furthermore, the efficiency of alternators, long transmission lines, distribution lines, and all appliances connected to the power system are affected by these changing characteristics. After a perturbation, synchronous machines attempt to regain equilibrium but at different rotor angles. Therefore, oscillations that are not damped completely may lead to an increase in low frequency oscillations in power networks, causing problems in system stability and reducing the power transfer capability of transmission lines [2,3,4]. The power system's low

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frequency oscillations are classified into two types, one with local area modes of oscillation that have a frequency range from 0.8 to 3 Hz and the other with inter-area modes of oscillations that range from 0.2 to 0.7 Hz [5].

This low frequency oscillation in the power system is one of the main reasons for small-signal instability, and to achieve stability of the system the low frequency must be completely damped by certain devices incorporated into the system. The aim of this paper is to incorporation a combination of STATCOM (static synchronous compensators) and PSS (Power System Stabilizer) into a multi-machine system to enhance small-signal stability, and this will be actualize by first modelling an IEEE 9-bus system, then followed by the modelling of a STACOM and PSS device which are finally incorporated into the IEEE 9-bus system using MATLAB Simulink.

An Overview of PSS and STATCOM

The stability of a power system is its ability to develop a restoring force which is equal or greater than the force responsible for the disturbance of the system to maintain the stability of the system. In power systems, according to [6], there are three main groups of power system stability which are, rotor angle stability, frequency stability, and voltage stability, the small-signal stability is an aspect of rotor angle stability, which is the ability of synchronous machines in a power system to remain in synchronism after a small, continuous disturbances like load or generation changes. The stability of a power system is of primary concern as it is expected that the synchronous machines which form large parts of the traditional power system must operate and maintain a synchronous state.

Perturbation in the system produces low frequency oscillations and affects electrical generation that could lead to unstable machines that trip other units and collapse the system [7]. Application of a PSS is a first measure to enhance the small signal stability. A PSS is the preferred method to improve the power system damping effect [8,9]; its installation is economical and effective for stabilizing low frequency oscillations within a system [8,10,11].

Power System Stabilizer (PSS)

A Power System Stabilizer (PSS) is a device that enhances power system stability (Small-Signal Stability) by damping low-frequency electromechanical oscillations in synchronous generators. It does this by providing supplementary control signals to the generator's excitation system, which are in phase with the rotor speed deviations to create a damping torque. A conventional PSS was presented for power system network's dynamic stability in [12].

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, $\mathrm{d_w}$, or its acceleration power, $\mathrm{P_a} = \mathrm{P_m} - \mathrm{P_{eo}}$ (difference between the mechanical power and the electrical power) [13].

The Generic Power System Stabilizer is modeled by the following nonlinear system:

Fig.1: The components of the Generic Power System Stabilizer

In order of the connection of the Simulink blocks we have 1 at the input as the rotor speed deviation, sensor, k is the overall gain, wash-out, lead-lag1, lead-lag2, limiter and 1 at the

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output is the Voltage stabilization (Vstab). To ensure robust damping, the PSS should provide a moderate phase advance at frequencies of interest 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 d_w 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 for the phase lag between the excitation voltage and the electrical torque of the synchronous machine [14].

Static Synchronous Compensators (STATCOM)

This is a reactive power compensation device, the basic function of the STATCOM is to compensate with the reactive power it provides in the power system, that is, the device provides large percent of the reactive power needed in the power system when connected to the grid. It therefore implies that to achieve a unity power factor in a power system then a STATCOM needs to connect to the system to supply all the reactive power needed by the load, keeping the reactive power from the grid system equal to zero. Below is a block diagram which illustrates how STATCOM is connected to the system, and it functions

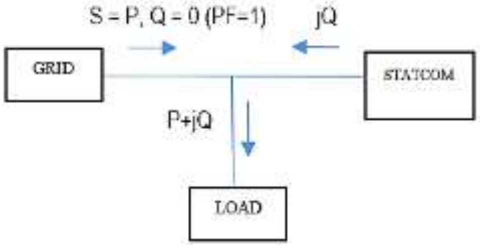

Fig.2: The principle of operation of Static Synchronous Compensators (STATCOM)

The function of the STATCOM is possible because of its controller, where the alpha/beta (α/β) and d/q transformation take place for the grid voltage, load current and the inverter current, also with the introduction of the phase lock loop using alpha/beta voltages. With the transformed values the DC bus controller, access current controller and the q-axis current controller is implemented, the final output of the controller is given for the pulse width modulation (PWM). Below is the block diagram of the STATCOM controller for a three-phase system

Modelling of the IEEE 9-bus system in MATLAB/Simulink

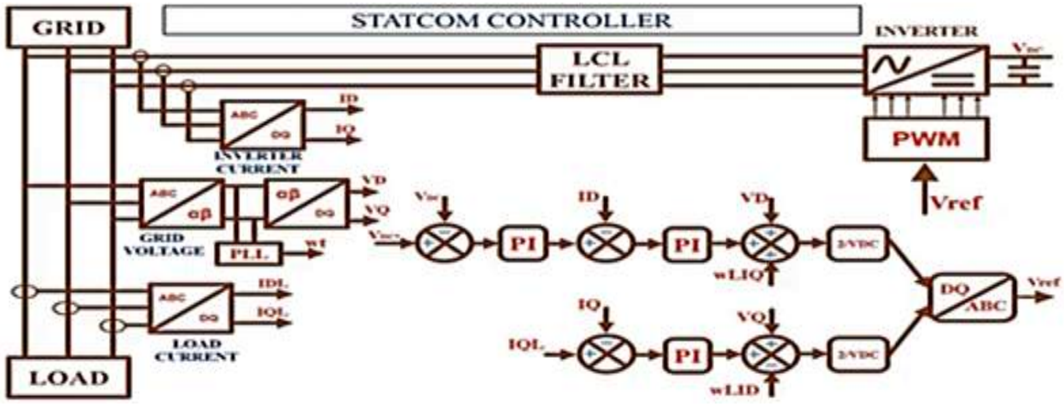

Fig.3: Three-phase STACOM controller

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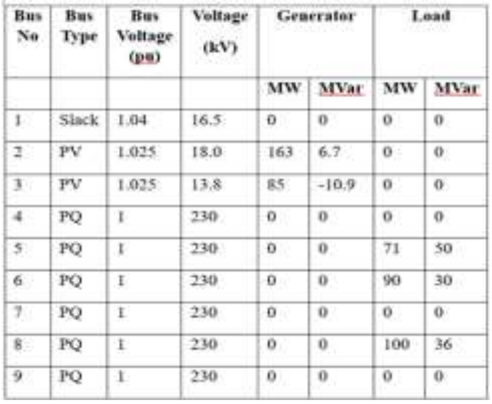
The modelling of the 9-bus system was achieved using the standard values of the IEEE 9-bus system, which are the bus data and line parameters. With the help of these values, we were able to compute the values for the positive and zero sequence for the respective lines of the 9-bus system. Below are the tables of values for the bus data, the line parameter and the line. Table 1: Bus data and line data for a 9-bus

Table 1: Bus data and line data for a 9-bus diagram of the system. IEEE system



Bus No	Bus Type	Bus Voltage (pu)	Voltage (kV)	Generator		Load	
				MW	MVar	MW	MVar
1	Slack	1.04	16.5	0	0	0	0
2	PV	1.025	18.0	163	6.7	0	0
3	PV	1.025	13.8	85	-10.9	0	0
4	PQ	1	230	0	0	0	0
5	PQ	1	230	0	0	71	50
6	PQ	1	230	0	0	90	30
7	PQ	1	230	0	0	0	0
8	PQ	1	230	0	0	100	36
9	PQ	1	230	0	0	0	0

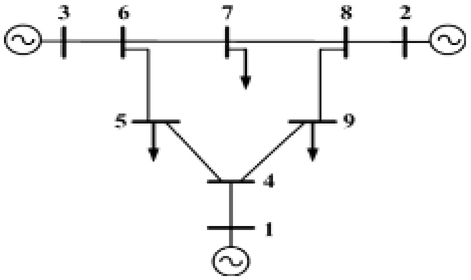


Fig.4: Line diagram of the IEEE 9-bus System

Calculation of Line Parameters

For the calculation of the IEEE 9-Bus system line parameters, we used the following values for the base apparent power and base voltage.

Base apparent power (S_b) = 100MVA
Base voltage (V_b) = 230kV

The following formula were used to obtain the line parameters which are:

Length of transmission line

$$L=\frac{\sqrt{XB}}{2\pi f}\text{x speed of light in km} \quad (1)$$

Where X is the line reactance and B is the line susceptance.

$$B_{actual}=B_{pu}xB_{base} \quad (2)$$

$$R_{actual}=R_{pu}XR_{base} \quad (3)$$

$$X_{actual}=X_{pu}xX_{base} \quad (4)$$

$$R_{base}=X_{base}=\frac{V_b^2}{S_b} \quad (5)$$

$$B_{base}==\frac{S_b}{V_b^2} \quad (6)$$

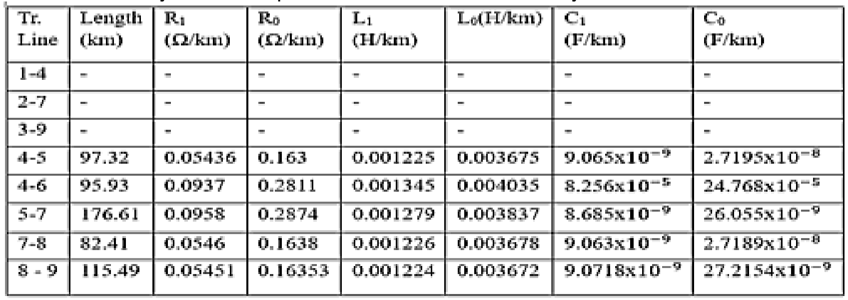
$$R_0 = 3R_1 \quad (7)$$

$$C_0=3C_1 \quad (8)$$

$$L_0=3L_1 \quad (9)$$

Below is the summary of the line parameters

Table 2: summary of the line parameters for a 9-bus IEEE system



Tr. Line	Length (km)	R_1 (Ω/km)	R_0 (Ω/km)	L_1 (H/km)	L_0(H/km)	C_1 (F/km)	C_0 (F/km)
1-4	-	-	-	-	-	-	-
2-7	-	-	-	-	-	-	-
3-9	-	-	-	-	-	-	-
4-5	97.32	0.05436	0.163	0.001225	0.003675	$9.065x10^{-9}$	$2.7195x10^{-8}$
4-6	95.93	0.0937	0.2811	0.001345	0.004035	$8.256x10^{-5}$	$24.768x10^{-5}$
5-7	176.61	0.0958	0.2874	0.001279	0.003837	$8.685x10^{-9}$	$26.055x10^{-9}$
7-8	82.41	0.0546	0.1638	0.001226	0.003678	$9.063x10^{-9}$	$2.7189x10^{-8}$
8 - 9	115.49	0.05451	0.16353	0.001224	0.003672	$9.0718x10^{-9}$	$27.2154x10^{-9}$

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Where the parameters with subscript one (R_1, L_1,C_1,) are the positive sequence while the ones with subscript zero (R_0, L_0,C_0) are the zero sequence for resistance, inductance and capacitance respectively,

Finally, we model the system on MATLAB Simulink, and we run the load flow for the 9-bus system. Below is the modelled system with the load flow result where the swing bus has an active power of 162.04MW and a reactive power of 1285.16MVar.

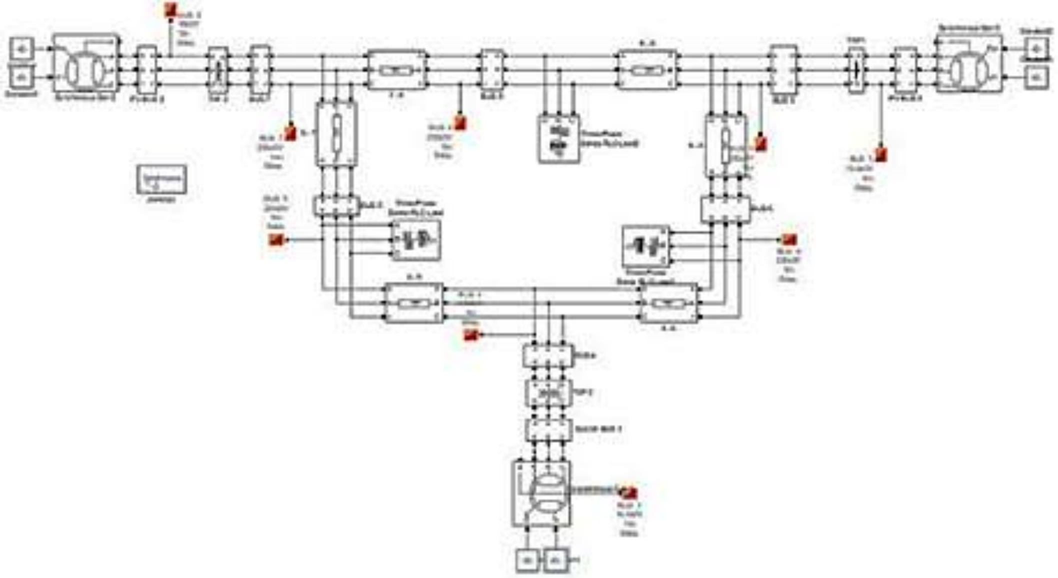
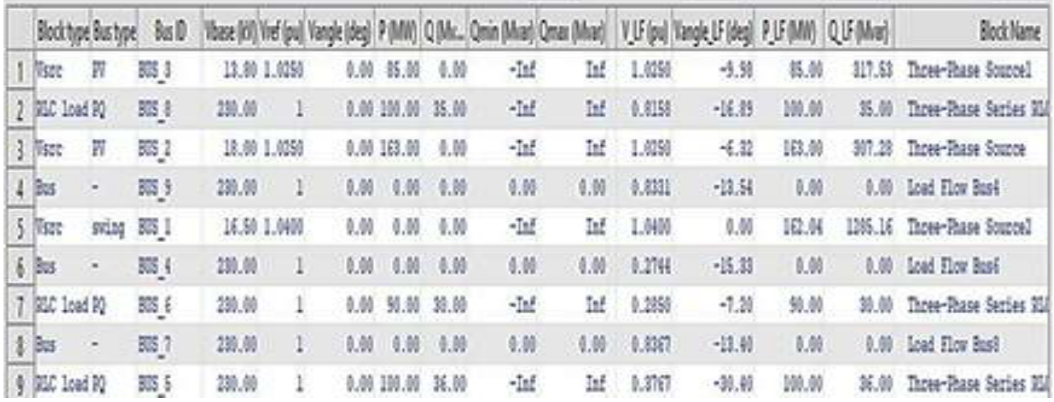


Figure 3.1.2: Model of an IEEE 9-bus power system in MATLAB Simulink

Table 3: Output for the load flow of the 9-bus system



	Block type	Bus type	Bus ID	Vbase (kV)	Vref (pu)	Vangle (deg)	P (MW)	Q (Mv...	Qmin (Mvar)	Qmax (Mvar)	V_LF (pu)	Vangle_LF (deg)	P_LF (MW)	Q_LF (Mvar)	Block Name
1	Vsrc	PV	BUS_3	13.80	1.0250	0.00	85.00	0.00	-Inf	Inf	1.0250	-9.98	85.00	317.53	Three-Phase Source1
2	RLC load	PQ	BUS_8	230.00	1	0.00	100.00	35.00	-Inf	Inf	0.8158	-16.89	100.00	35.00	Three-Phase Series RL
3	Vsrc	PV	BUS_2	18.00	1.0250	0.00	163.00	0.00	-Inf	Inf	1.0250	-6.32	163.00	307.28	Three-Phase Source
4	Bus	-	BUS_9	230.00	1	0.00	0.00	0.00	0.00	0.00	0.8331	-13.54	0.00	0.00	Load Flow Bus4
5	Vsrc	swing	BUS_1	16.50	1.0400	0.00	0.00	0.00	-Inf	Inf	1.0400	0.00	162.04	1285.16	Three-Phase Source1
6	Bus	-	BUS_4	230.00	1	0.00	0.00	0.00	0.00	0.00	0.2744	-15.33	0.00	0.00	Load Flow Bus6
7	RLC load	PQ	BUS_6	230.00	1	0.00	90.00	30.00	-Inf	Inf	0.2858	-7.20	90.00	30.00	Three-Phase Series RL
8	Bus	-	BUS_7	230.00	1	0.00	0.00	0.00	0.00	0.00	0.8367	-13.40	0.00	0.00	Load Flow Bus8
9	RLC load	PQ	BUS_5	230.00	1	0.00	100.00	36.00	-Inf	Inf	0.3767	-30.40	100.00	36.00	Three-Phase Series RL

MODELLING THE INTEGRATED SYSTEM IN MATLAB/SIMULINK

Modelling of the STATCOM controller in MATLAB/Simulink

Modelling of the STATCOM controller separately in MATLAB/Simulink was achieved using the various Simulink blocks to implement the alpha-beta (α/β) and d-q transformation, the transformed valves with the phase lock loop was use to also implement the DC bus controller,

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access current controller and the q-axis current controller and the final output of the system was feed into the pulse width modulation (PWM) device connected the inverter. For the STACOM system we used a single supply to represent the grid but later we are going to incorporate the STATCOM system into the 9-bus system. The system was run with ode23t (mod. Stiff/Trapezoidal) solver with a relative tolerance of 1e-3. Below is the modelled STATCOM system with active and reactive power output for the grid, load and STATCOM device.

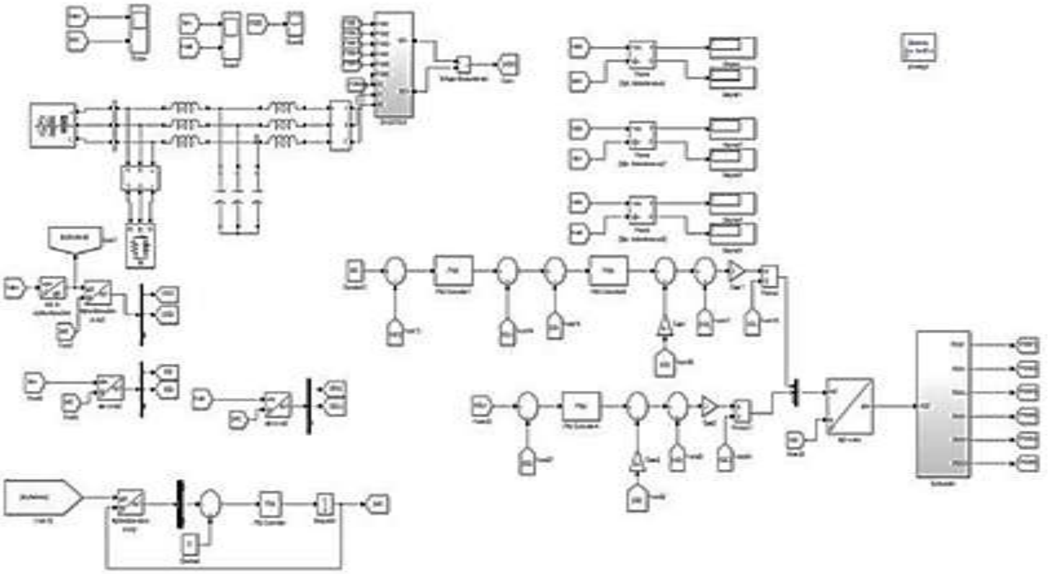

Fig.5: STATCOM device model in MATLAB/Simulink

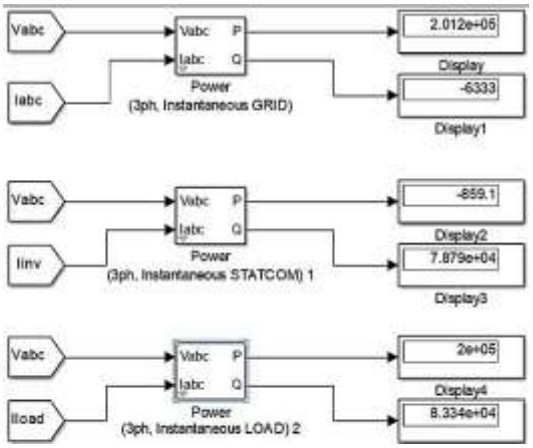

Fig.6: Active and Reactive power output for the grid, load and STATCOM device

From the output display it can be seen that the STATCOM device actually compensated with the reactive power from the STATCOM instantaneous power display we can see a reactive power of 78790Var as against the active power which is -859.1W while for the instantaneous power output displayed from the Grid we can see a supply of 201200W active power as against -6333Var the reactive power while implies the Grip supply mainly the active power to the system.

Modelling of the Power System Stabilizer in MATLAB/Simulink

The modelling of a Power System Stabilizer (PSS) for a power system is always achieved with the aid of an excitation system. For the 9-bus power system we were able to model the PSS system comprising of a multi-band power system stabilizer, excitation system, constant block and a bus selector which take the various input signals from the synchronous generator to

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the input of the excitation system and the power system stabilizer.

The multi-band PSS (MB-PSS) is generally preferred over the generic PSS for a 9-bus power system (a multi-machine system) because it provides better damping across a wider range of oscillation frequencies, including local, inter-area, and global modes. The PSS was configured using the standard IEEE values for the system and finally the system was incorporated into the 9-bus system. Below is the section of the power system showing the Power System Stabilizer (PSS).

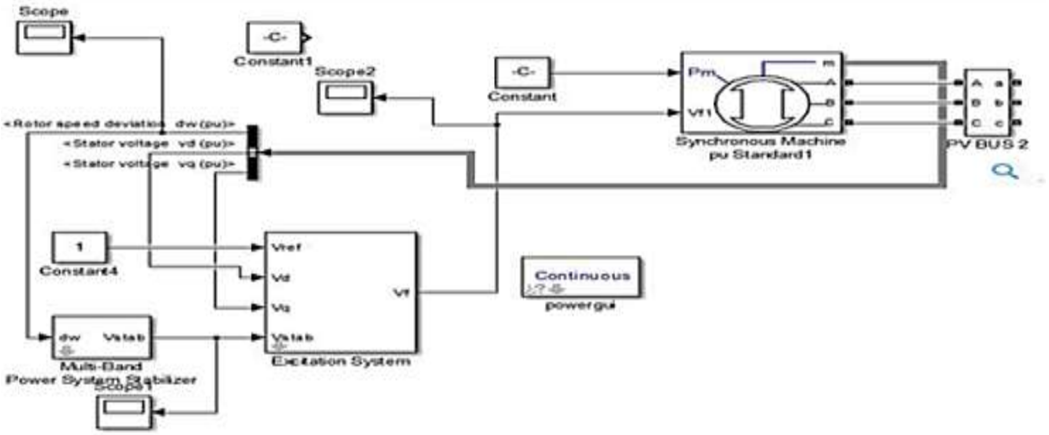

Fig.7: A section of the Power System Stabilizer taking input signal from the synchronous generator

Integration of the STATCOM and Power System Stabilizer (PSS).

Finally, after the STATCOM and PSS were successfully modelled, it was integrated into the 9-bus power system, where the STATCOM was connected at bus 4 and the PSS was connected to synchronous generator 2. The STATCOM system was connected to bus 4 to improve system performance, voltage stability and the likes. But the optimal location for a STATCOM varies depending on the specific goal, studies have revealed benefits of using this location, which include enhancing voltage profiles and reducing fault impact. Below is the integrated system.

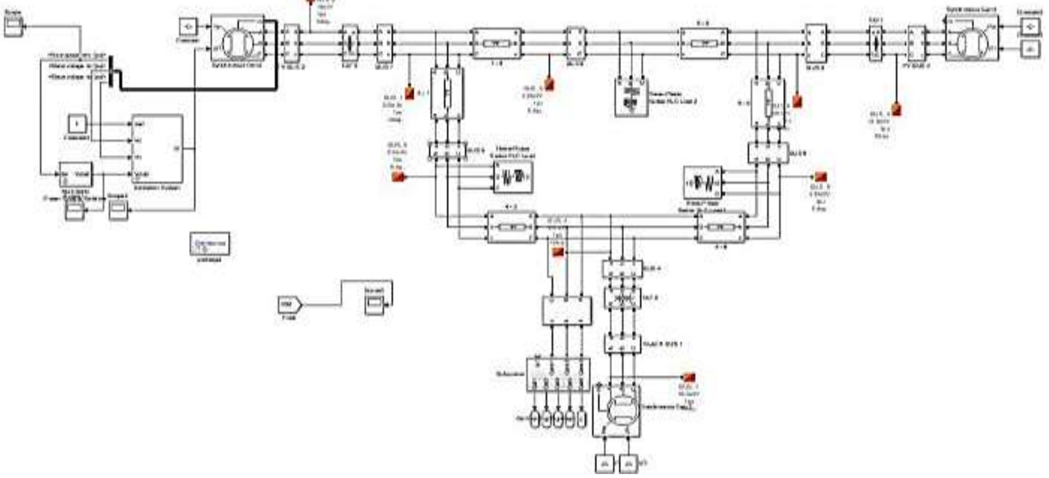

Fig.8: STATCOM and PSS Integrated into the Multi-machine System (9-Bus System)

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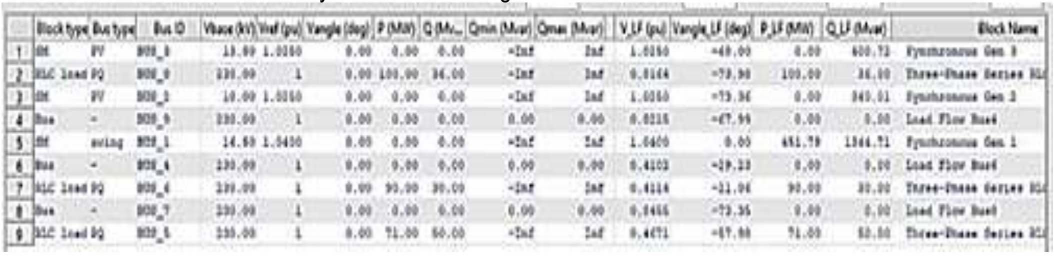
After the successful integration of the STATCOM and PSS we ran a load flow, and we discovered an improvement in the voltage profile at the various buses as compared to the 9-bus system when the two devices were not yet integrated into the system. Below is the output of the load flow with integration of the STACOM and PSS.

Table 4: Load flow of the 9-bus system with the integration of STATCOM and PSS



	Block type	Bus type	Bus ID	Vbase (kV)	Vref (pu)	Vangle (deg)	P (MW)	Q (Mv...	Qmin (Mvar)	Qmax (Mvar)	V_LF (pu)	Vangle_LF (deg)	P_LF (MW)	Q_LF (Mvar)	Block Name
1	SM	PV	BUS_3	13.80	1.0250	0.00	0.00	0.00	-Inf	Inf	1.0250	-48.00	0.00	400.72	Synchronous Gen 3
2	RLC load	PQ	BUS_8	230.00	1	0.00	100.00	36.00	-Inf	Inf	0.8164	-73.90	100.00	36.00	Three-Phase Series RL
3	SM	PV	BUS_2	18.00	1.0250	0.00	0.00	0.00	-Inf	Inf	1.0250	-73.36	0.00	340.01	Synchronous Gen 2
4	Bus	-	BUS_9	230.00	1	0.00	0.00	0.00	0.00	0.00	0.8215	-47.99	0.00	0.00	Load Flow Bus6
5	SM	swing	BUS_1	16.50	1.0400	0.00	0.00	0.00	-Inf	Inf	1.0400	0.00	451.79	1344.71	Synchronous Gen 1
6	Bus	-	BUS_4	230.00	1	0.00	0.00	0.00	0.00	0.00	0.4103	-19.23	0.00	0.00	Load Flow Bus4
7	RLC load	PQ	BUS_6	230.00	1	0.00	90.00	30.00	-Inf	Inf	0.4114	-11.96	90.00	30.00	Three-Phase Series RL
8	Bus	-	BUS_7	230.00	1	0.00	0.00	0.00	0.00	0.00	0.8455	-73.35	0.00	0.00	Load Flow Bus8
9	RLC load	PQ	BUS_5	230.00	1	0.00	71.00	60.00	-Inf	Inf	0.4471	-67.88	71.00	50.00	Three-Phase Series RL

RESULT AND DISCUSSION

With the whole system integrated, that is, the STATCOM and the PSS connected to Bus 4 and synchronous generator 2 of the 9-Bus power system respectively. To analyze the improvement in damping ratio and mode shapes, prior to application of any disturbance to the system, we carried out a procedure to check for the improvement in the system. First, we run a simulation without the PSS connected to the synchronous generator 2 using electrical power (P_e) and rotor speed as input to the bus selection from the synchronous generator to observe the damping ratio and the mode shapes respectively. Below were the plots which displaced output of the electrical power input and rotor speed (ω_m) for the damping ratio and mode shapes analysis respectively.

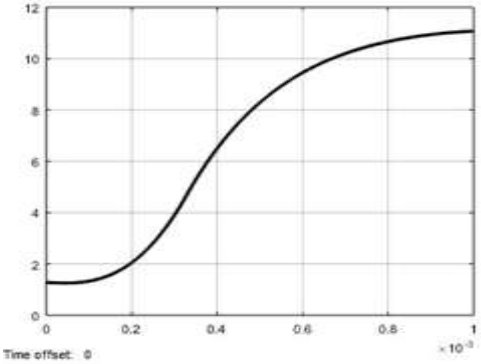


Fig.9: Plot of Electrical power (P_e) without PSS and STATCOM connected to System

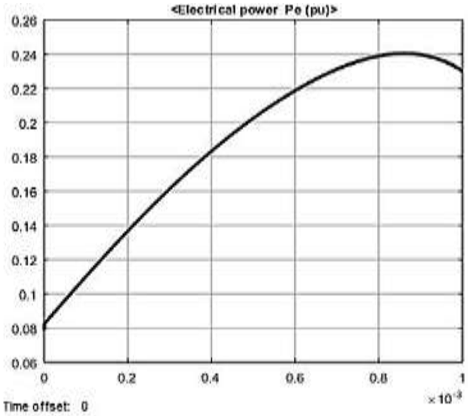


Fig.10: Plot of rotor speed (ω_m) input without PSS and STATCOM connected to the system

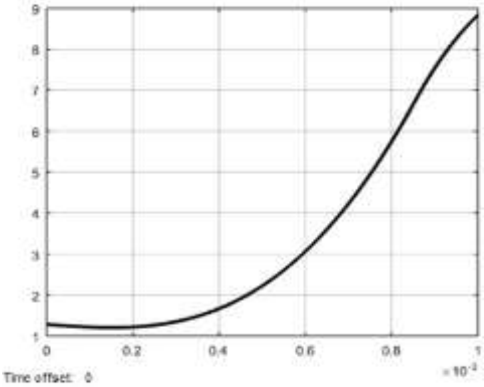


Fig.11: Output Plot of Electrical power (P_e) input with PSS and STATCOM connected to System immediately after the Power System Stabilizer

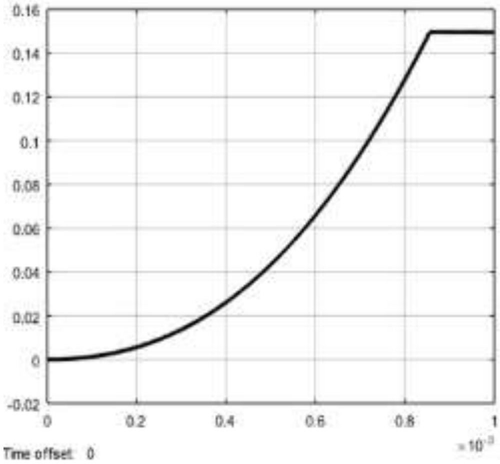


Fig.12: Output Plot of Electrical power (P_e) input with PSS and STATCOM connected to System immediately after the Excitation System

CONCLUSION

In conclusion, it is of great importance to take into consideration the integration of certain control systems-the likes of PSS and STATCOM which enhances the stability of a multi-machine system, like the 9-bus system we have model, and even more larger systems to mitigate any disturbances that may be introduced in the system. In essence, the importance of the stability of a system cannot be overemphasized. For the future it is also important we take into consideration to research into new control enhancement systems that can also improve the stability of the increasing penetration of renewable energy into the grid system.

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