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Comparative Study of Synchronous Machine, Model 1.0 and Model 1.1 in Transient Stability Studies with and without PSS

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Abstract— **This paper represents the modelling differences of Single Machine Infinite Bus (SMIB) system with a Power System Stabiliser (PSS) developed in MATLAB/SIMULINK software. In this model the synchronous generator is represented by Model 1.0 and Model 1.1 in which they have only generator main field winding for the former and a damper winding on q axis in addition to the main field winding in the latter. This paper provides a view into the fact how power system returns to normal or stable operation after being subjected to various kinds of disturbances.**

Keywords— ***Model 1.0, model 1.1, Single Machine Infinite Bus (SMIB), modelling and simulation, MATLAB/SIMULINK, Power System Stabilizer (PSS).***

I. INTRODUCTION

A synchronous machine is a one which rotates at a constant speed called as the *synchronous speed*. These machines that rotate at a speed which is fixed by the supply frequency and the number of poles. A.C generators are usually known as *alternators (synchronous generators).*A synchronous generator is a machine which converts the mechanical power input from prime mover to an A.C electrical power. A synchronous motor does exact vice versa functioning of synchronous generator. 3-phase synchronous generators are widely used so as to have improved efficiency in generation, transmission and distribution. For bulk power generation huge synchronous generators of few Mega Watts are used in thermal, nuclear, hydro power plants and in recent days even in wind turbines.

A synchronous motor can consume leading or lagging reactive current from AC source. A synchronous machine is doubly excited machine. Direct current is passed through the field winding as excitation for synchronous machine by an *exciter*. The dc output of the exciter is fed to the field winding on the rotor through slip rings and brushes. This is applicable to small machines. For medium sized machines instead of dc exciter, *AC excitation system* is used. And for large machines *brushless excitation systems* are used.

Any synchronous machine installed in a power system may be subjected to various anomalous conditions and disturbances. These disturbances will give rise to mechanical as well as electrical transients. These transients rise due to switching, sudden changes in load, line to ground faults, line to line faults, etc. these faults produce large mechanical stress and may damage the machine. Hence the machine also loses synchronism in the system. It is necessary to analyze machine behaviour under these faulty situations. This analysis alleviate the severity of faults by selecting appropriate schemes, relays, circuit breakers, Power System Stabilizers(PSS), FACTS devices and avert the consequences in minimum possible time.

Considering all the above factors, modelling of synchronous machine for simulating and studying the effects on system is of primary importance. Modelling a synchronous machine, putting it through the susceptible faults will lead to the way it behaves in the system. But modelling is done with the appropriate degree of detailing and complexity based on the requirement and application.

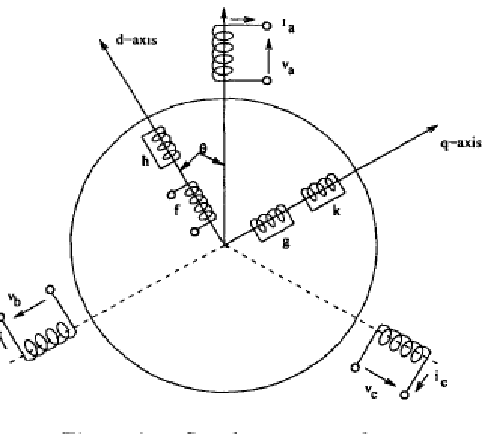

Fig.1: Representation of a synchronous machine

The synchronous machine considered above has three phase armature windings (a, b and c) on stator and four windings on the rotor including the field winding '*f*'. The eddy current effects in the rotor or damper circuits in the salient pole machine are represented by a set of coils with constant parameters. Three damper coils, '*h*' in the d-axis and g, k on the q-axis respectively. The number of damper coils represented can vary from zero to many [1].

Depending on the degree of detailing used for modelling, the number of rotor windings and corresponding state variables can vary from one to six. Models are divided based on varying degrees of complexity.

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1) Classical model (Model 0.0)
2) Field circuit only (Model 1.0)
3) Field circuit with one equivalent damper on q-axis (Model 1.1)
4) Field circuit with one equivalent damper on d-axis
   a. Model 2.1 (one damper on q-axis)
   b. Model 2.2 (two dampers on q-axis)
5) Field circuit with two equivalent damper circuits on d –axis
   a. Model 3.2 (with two dampers on q-axis)
   b. Model 3.3 (with three dampers on q-axis)

It is to be noted that in classification of the machine models, the first number indicates the number of windings on the d-axis while the second number indicates the number of windings on q-axis. Model 1.0 and model 1.1 are considered are considered in the following studies [1].

A. Abbreviations and Acronyms

Table I

δ	Rotor angle of synchronous generator in radians
S_m	Generator slip in p.u.
S_{mo}	Initial operating slip in p.u.
ω_B	Rotor speed deviation in rad/sec
T_m	Mechanical power input in p.u.
T_e	Electrical power output in p.u.
E_{fd}	Excitation system voltage in p.u.
V_t	Generator terminal voltage
E_b	Infinite-bus voltage
H	Inertia constant
D	Damping coefficient
T'_{do}	Open circuit d-axis time constant in sec
T'_{qo}	Open circuit q-axis time constant in sec
x_d	d-axis synchronous reactance in p.u.
x'_d	d-axis transient reactance in p.u.
x_q	q-axis synchronous reactance in p.u.
x'_q	q-axis transient reactance in p.u.
V_{pss}	Stabilizing signal from power system stabilizer
T_W	Washout time constant

B. Equations

Synchronous machine analysis-

In a power system many large generators operate in parallel. Considering the operation of a machine in such a large system is of great interest and high importance [2]. The capacity of the system is so large that its voltage and frequency can be considered as constant. So the addition/removal a machine or load does not contribute for the change in voltage or frequency. The system behaves like a large generator having virtually zero internal impedance and infinite rotational inertia. Such a system is called the *Infinite Bus* [2].

A single line representation of a single machine infinite bus (SMIB) system is shown in Fig 1. The generator considered is fitted with an excitation system. The line resistance is neglected. The generator and excitation system can be modelled as a fourth-order system with load angle - $\Delta\delta$, the rotor speed - $\Delta\omega$, the internal voltage of the generator – $E_q^{'}$, the field voltage – E_{fd} ,the internal voltage of the generator – $E_d^{'}$ and Electrical torque T_e as the state variables [1].

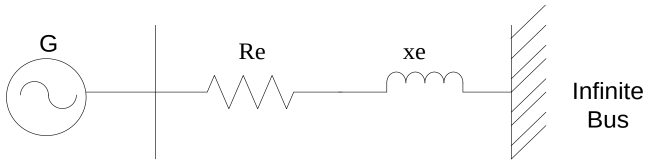

Fig.2: A single machine infinite bus system

The various system equations are as follows:

$$\frac{d\delta}{dt} = \omega_B\left(S_m - S_{m0}\right) \quad (1)$$

$$\frac{dS_m}{dt} = \frac{1}{2H}\left[-D\left(S_m - S_{m0}\right) + T_m - T_e\right] \quad (2)$$

$$\frac{dE_q^{'}}{dt} = \frac{1}{T_{do}^{'}}\left[-E_q^{'} + \left(x_d - x_d^{'}\right)i_d + E_{fd}\right] \quad (3)$$

$$\frac{dE'_d}{dt} = \frac{1}{T'_{qo}}\left[-E'_d - \left(x_q - x'_q\right)i_q\right] \quad (4)$$

$$\frac{dE_{fd}^{'}}{dt} = \frac{1}{T_E}\left[\left(V_{ref} - V\right)K_E - E_{fd}\right] \quad (5)$$

The electrical torque T_e is expressed in terms of variables E_q', E_q', i_q and i_d as:

$$T_e = E_d' i_d + E_q' i_q + \left(x_d' - x_q'\right) i_d i_q \quad (6)$$

For a lossless network, the stator algebraic equations and the network equations are expressed as:

$$E_q^{'} + x_d^{'} i_d = v_q \quad (7)$$

$$-x_q^{'} i_q = v_d \quad (8)$$

$$v_q = -x_e i_d + E_b cos\delta \quad (9)$$

$$v_d = -x_e i_q - E_b sin\delta \quad (10)$$

Solving the above equations, the variables and can be obtained as:

$$i_d = \frac{E_b Cos\delta - E_q^{'}}{x_e + x_q^{'}} \quad (11)$$

$$i_q = \frac{E_b Sin\delta - E_d^{'}}{x_e + x_q^{'}} \quad (12)$$

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C. Fault Simulations

a) Step change in Mechanical Input(T_m)- The first disturbance to which the system is subjected is a step change of mechanical torque with a change of 0.1pu was indeed stable, the system was kind of settling down to an operating point with the use of PSS. But without the use of PSS the system does not settle down because the new operating point is not small signal stable [1].

b) Change in Reference Voltage (V_{ref}) -
The reference voltage is set according to E_{fd} value and the step change in V_{ref} this leads to unstable excitation field which is again cleared with the use of PSS ,$V_{ref}=(E_{fdo}/K_e)+V_{to}$ [1].

c) Change in Bus Voltage (E_b) - Here the Voltage at the receiving end is changed at step value. This causes a fault in the system and using PSS a new steady state value is obtained [1].

d) 3 phase fault at generator terminal -
A 3 phase fault is applied at the generator terminal as shown in the figure below and is cleared after few cycles. The operating points of Pg and x_e are given and hence the system is initially at equilibrium. After few cycles the system is stabilized using PSS within the PSS limits of -0.05 to +0.05[1].

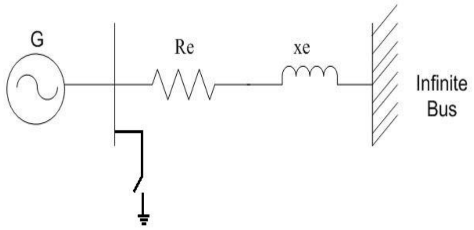

Fig.3 : Three phase fault at generator terminal

e) Control System block of PSS-
To damp the electromechanical oscillations Power System Stabilizers (PSS) are the best remedy considered since many years. The use of fast acting high gain AVR's and the evolution of large interconnected power systems with transfer of bulk power across weak transmission links have further aggravated the problem of low frequency oscillations [3]. Continuously varying operating conditions and network parameters of the power system result in fluctuation of system dynamics. So this makes the designing of damping controllers for power systems a challenging task.

A commonly used conventional lead-lag PSS (CPSS) is considered in this study. Its structure is shown in Fig. 4. It consists of a gain block with gain K_{pss}, a signal washout block, and two-stage phase compensation block with time constants T1, T2 and T3, T4. In this structure, *Tw* is the washout time constant; $\Delta\omega$ is the speed deviation and V_S is the stabilizing signal output of PSS [4].

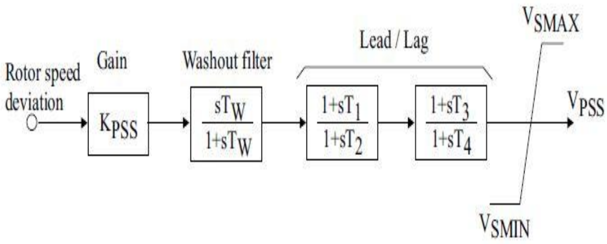

Fig.4 : Block diagram of PSS

II. RESULTS

The results show the behaviour of various machine parameters like rotor angle (δ), slip, terminal voltage (V_t) with respect to time when systems is subjected to both small signal and large signal faults. The graphs compare the variations in the parameters of the synchronous machine for Model 1.0 and Model 1.1.

a) Comparison of Model 1.0 and Model 1.1 **with** *PSS*

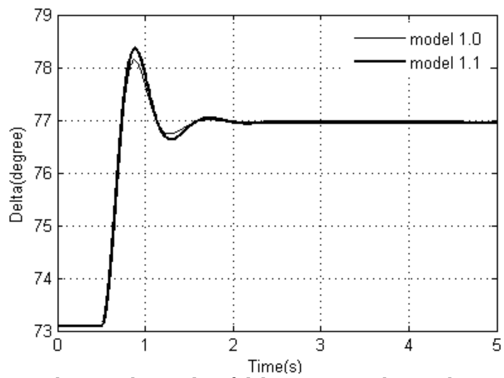

Fig.5: showing the results of delta vs time with step change in T_m

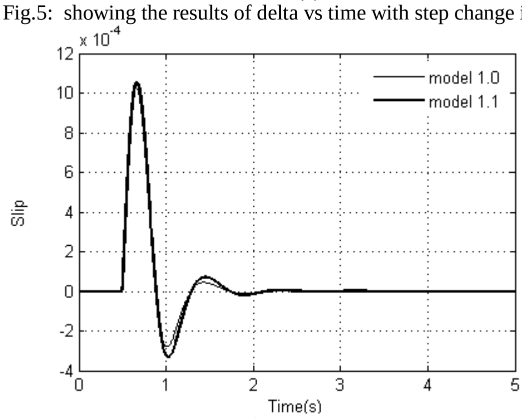

Fig.6: showing the results of slip vs time with step change in T_m

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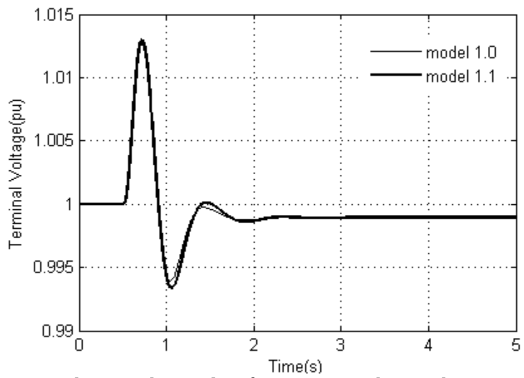

Fig.7: showing the results of V_t vs time with step change in T_m

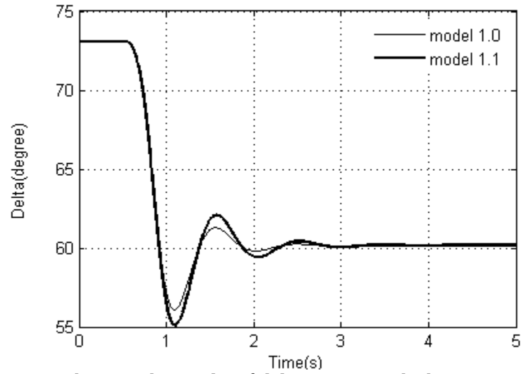

Fig.8: showing the results of delta vs time with change in V_{ref}

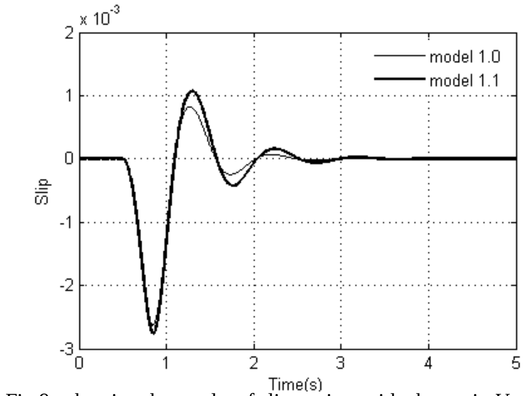

Fig.9: showing the results of slip vs time with change in V_{ref}

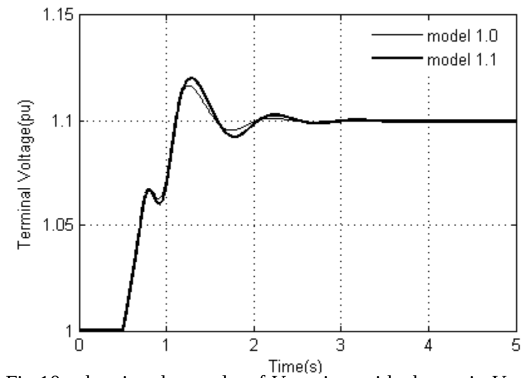

Fig.10: showing the results of V_t vs time with change in V_{ref}

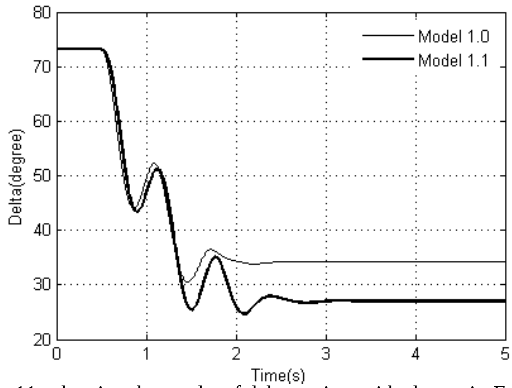

Fig.11: showing the results of delta vs time with change in E_b

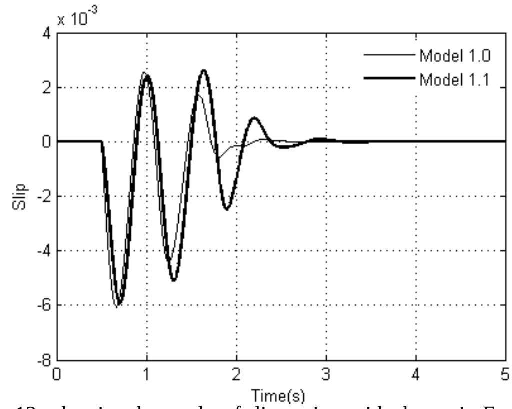

Fig.12: showing the results of slip vs time with change in E_b

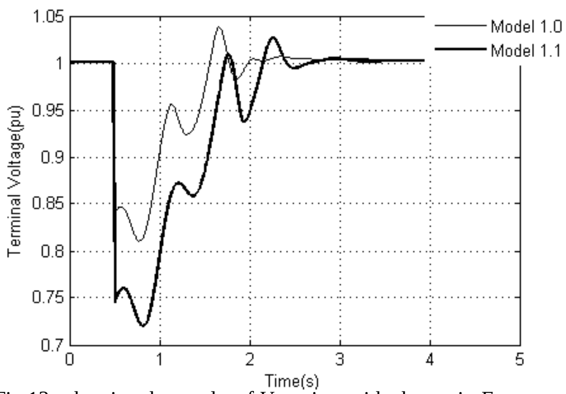

Fig.13: showing the results of V_t vs time with change in E_b

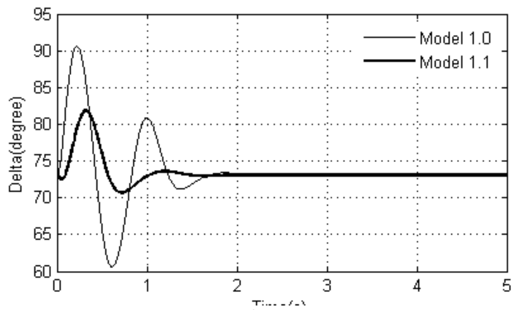

Fig.14: showing the results of delta vs time system subjected to a 3phase fault

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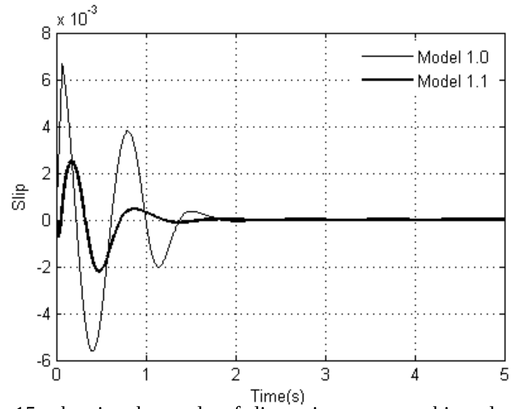

Fig.15: showing the results of slip vs time system subjected to a 3phase fault

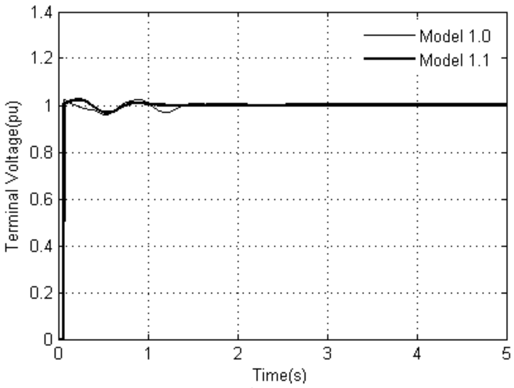

Fig.16: showing the results of V_t vs time system subjected to a 3phase fault

b) Comparison of Model 1.0 and Model 1.1 without PSS

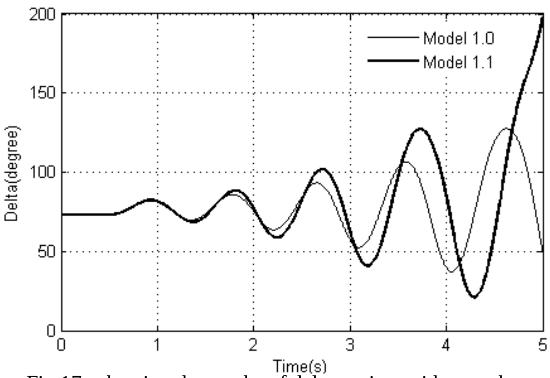

Fig.17: showing the results of delta vs time with step change in T_m

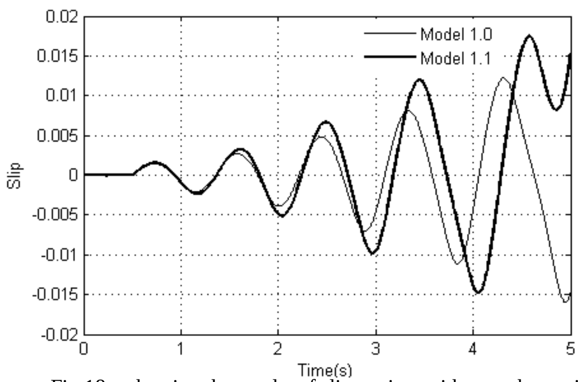

Fig.18: showing the results of slip vs time with step change in T_m

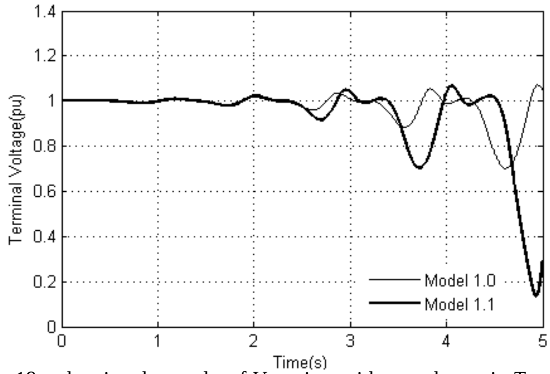

Fig.19: showing the results of V_t vs time with step change in T_m

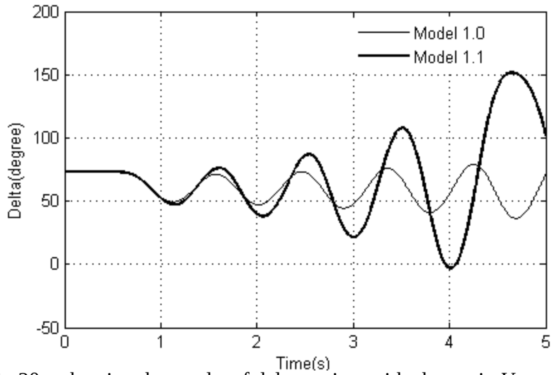

Fig.20: showing the results of delta vs time with change in V_{ref}

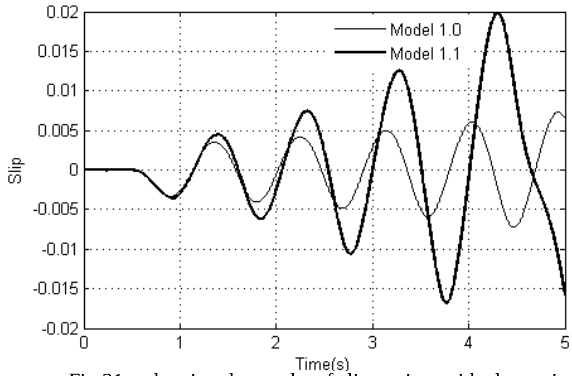

Fig.21: showing the results of slip vs time with change in V_{ref}

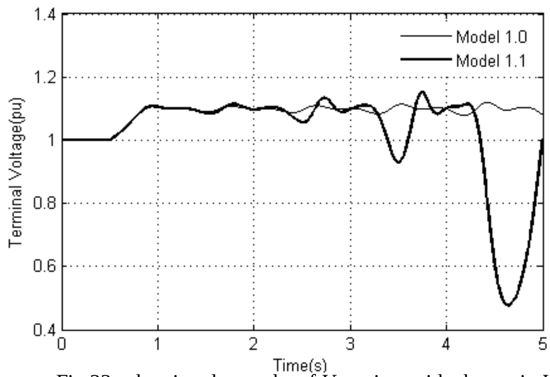

Fig.22: showing the results of V_t vs time with change in V_{ref}

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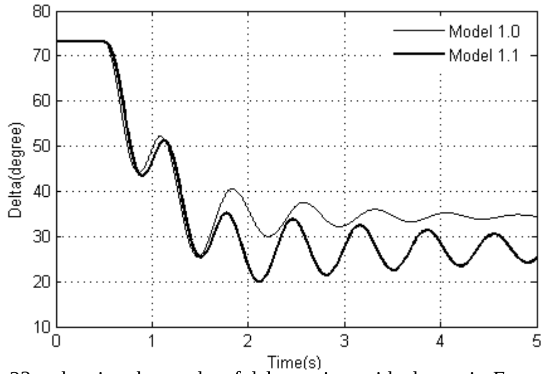

Fig.23: showing the results of delta vs time with change in E_b

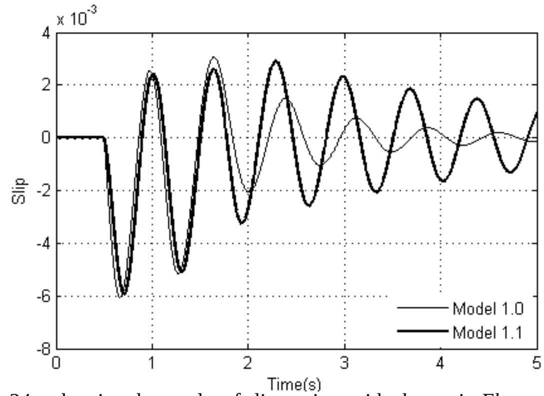

Fig.24: showing the results of slip vs time with change in *Eb*

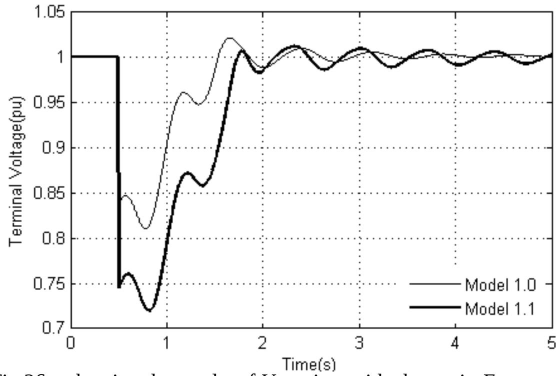

Fig.26: showing the results of V_t vs time with change in E_b

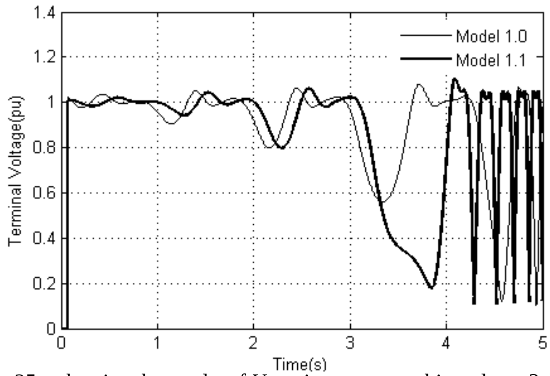

Fig.25: showing the results of V_t vs time system subjected to a 3phase fault

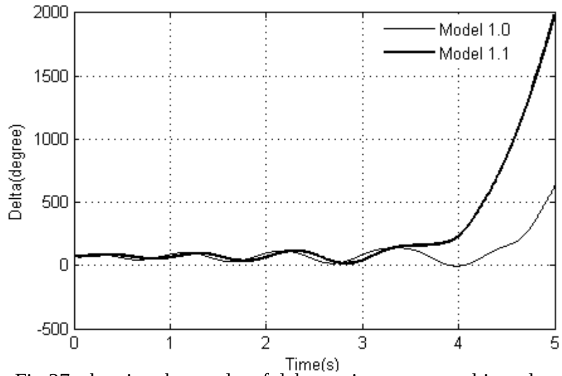

Fig.27: showing the results of delta vs time system subjected to a 3phase fault

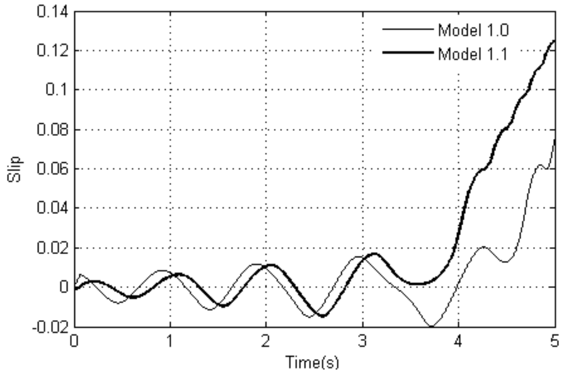

Fig.28: showing the results of slip vs time system subjected to a 3phase fault

III. OBSERVATIONS

In Model 1.0 by letting $x_q' = x_q$ (if saliency is not to be considered) and $T_{qo}' \neq 0$ Equation (4) becomes 0 (Note: Under steady state conditions) with the initial conditions at zero E_d' remains 0 throughout as long as $T_{qo}' > 0$. The voltage behind the transient reactance has only one component i.e E_q' (Flux decay due to armature reactance). Therefore model 1.0 comprises of only q-axis. But in model 1.1 the transient effects are accounted for, while the sub-transient effects are neglected and the machine will have two stator and rotor circuits. So here $x_q' = x_d'$. PSS is used for maintaining the steady state in the above graphs.

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IV. CONCLUSION

Power system stabilizer (PSS) is a low cost solution to the damping of low frequency oscillations produced in the system. Moreover, PSS helps in improving dynamic stability of the system without degrading the system's performance in case of faults or transients. As far as we have simulated the system the system with no PSS subjected to faults, we find that the parameters over-damp with time and never attain stability. So a PSS is must for the power system for its dynamic stability. From the above graphs it can inferred there are some subtle difference in the variation of parameters with time for Model 1.0 and Model 1.1. This is due to the fact that Model 1.0 considers some assumptions in calculation of machine parameters but whereas Model 1.1 is better and realistic. So simulation of synchronous machine using higher version models may give substantial and more accurate results. From the above graphs we observe that the transients over-damp and won't settle if PSS is not included in the system. So PSS is a must to bring the system to a stable state.

V. APPENDIX

The generator parameters in per unit are as follows:
$X_d = 1.79$
$X_q = 1.66$
$X'_d = 0.355$
$X'_q = 0.57$
$R_s = 0.0048$
$T'_{d0} = 7.9s$
$T'_{q0} = 0.41s$
$H = 3.77$
$D= 2$
$T_m = 0.8s$

The exciter parameters in per unit are as follows:
$T_E = 0.052s$
$K_E = 400$
$V_{Rmax} = 1$
$V_{Rmin} = -1$

The PSS parameters are:
wash-out network constants: $Ks = 120$; $Tw = 1$
lead-lag network : $T1 = 0.024$; $T2 = 0.002$
lag-lead network: $T3 = 0.024$; $T4 = 0.24$
The external line parameters are:
$r_e =0$ $x_e = 0.4$

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