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Evaluating the Effect of Various Faults on Transient Stability Using a Single Machine Equivalent (SIME)

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ABSTRACT: *In this work, a single machine equivalent model equipped with static variable compensator in the middle of the transmission line is simulated with simpowersystem. Critical clearing time of this non linear model is estimated with statistical pattern recognition. Classical model of this model is used to compute this critical clearing time using Equal Area Criteria with 4th order Runge Kutta numerical method and simulated in MATLAB 7.5 environment. Different types of faults were introduced at the busbar and were analyzed. The results show that classical critical clearing time estimation for the three-phase-to-ground fault was 0.6308 sec followed by the classical critical clearing time for the double-line-to-ground fault which was 0.8754sec and lastly the single-line-to-ground fault has its classical critical clearing time as 1.89 secs. The three-phase fault was observed to be the severest of all the faults.*

Keywords - *Power System Stability, Transient Stability, Critical Clearing time, Excursion*

I. INTRODUCTION

Power system stability is defined as that property of a power system that enables it to remain in a stable equilibrium state under normal operating conditions and to regain an acceptable equilibrium state after being subjected to a disturbance [1]. Transient stability is a type of power system stability phenomena [2] and the fastest to develop after inception of a disturbance. The planning and maintenance of a secured power system operation depends a lot on its transient satiability, hence transient stability studies play a vital role in providing secured operating configurations in power system networks [3]. Transient stability is defined as the ability of a power system to maintain synchronous operation of the machine when subjected to a large disturbance [4].

The occurrence of a transient instability problem may result to large excursion on the system machine rotor angle. If corrective action fails, loss of synchronism among machines may result in total system collapse [5]. The quality of electricity supply is therefore measured amongst other factors, by the ability of the power system to clear faults before they cause damage to the power system equipment. The time at which fault is cleared before it causes damage on the power system is known as critical clearing time (CCT) [6].

II. MATERIALS AND METHODS

The rotor mechanical dynamics are represented by the Swing equations which were the critical equations used in this analysis [7].

$$2H\frac{d\omega}{dt} = T_m - T_e - D\omega \quad (1)$$

$$\frac{d\delta}{dt} = \omega \quad (2)$$

Where H = per unit inertia constant, D = Damping Coefficient, ω = rotor angle of the generator, δ = angular speed of the generator, T_m = Mechanical torque input, and T_e = Electrical torque output.

$$\delta_c = \frac{\pi f P}{2H} \cdot t_c^2 + \delta_o \quad (3)$$

Where δ_c = Critical clearing angle, H = Machine inertia, t_c = Critical Clearing time, f = frequency, and δ_o = initial corresponding load angle and P = power supplied.

A model of single machine equivalent (SIME) which was used to study the effects of various faults on transient stability of power system is shown in Fig.1

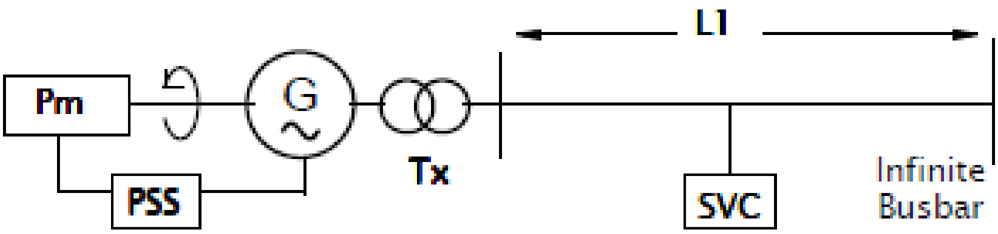

Figure 1: A single line diagram model of single machine equivalent (SIME)

2.1 Simulation of SIME Model with Simpowersystem

Various components of the model of single machine connected to infinite busbar as in Fig. 1 have been modeled in MATLAB under the simpowersystem toolbox. These components include the turbine synchronous generator, the power system stabilizer (PSS), static variable compensator (SVC), the transformer, and the transmission line. This system was configured as shown in Fig. 2. In the configured simpowersystem, the SVC is placed in the middle of the line and fault breaker is connected to the generator busbar to initiate any type of fault and also clear it when required.

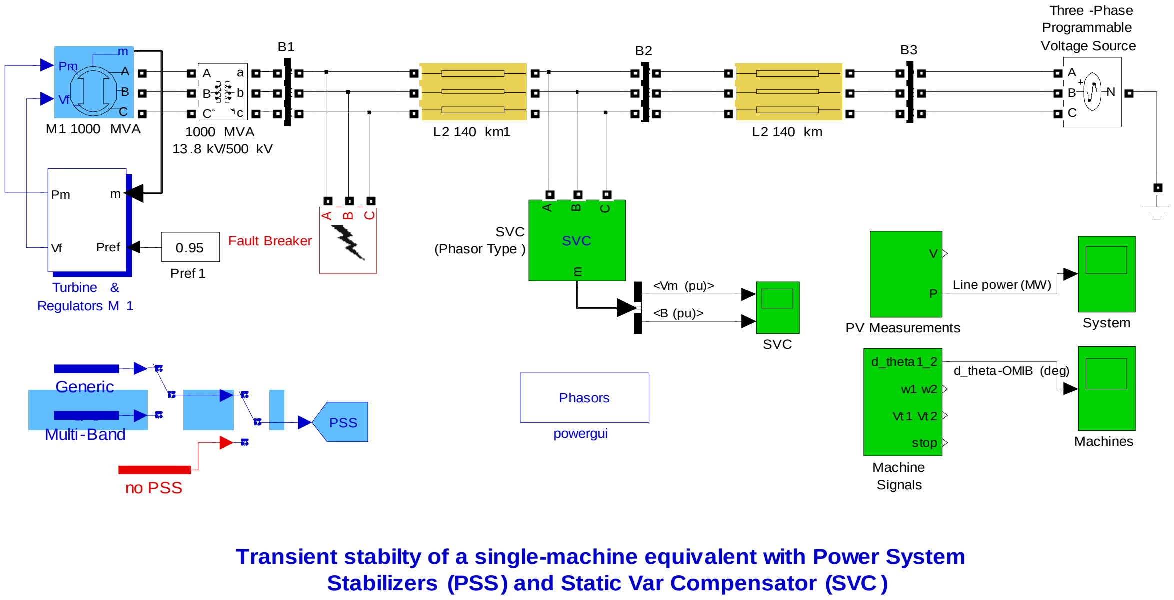

Figure 2: single-machine equivalent with Power System Stabilizers (PSS) and Static Var Compensator (SVC)

2.2 Loadflow simulation

The powergui window in the simpowersystem configuration solves the load flow through initial guess of the load flow and then iterates to get the actual load flow values at the machine terminals and buses, other quantities like the machine rotor angle, machine terminal voltage and current flowing in all the phases during steady state are also solved. All the required initialization quantities are then keyed in for transient stability simulation. Some of these calculated quantities like the initial rotor angle, the machine terminal power and voltage are used to calculate the electrical power developed by the generator which will be used to estimate the critical clearing time of faults using classical single machine model.

2.3 Transient stability simulation of faults

The transient stabilities of the following types of faults were simulated to study the effect of the PSS and SVC during fault transient; (i) Single phase to ground fault, (ii) Double Line to Ground fault and (iii) Three-phase to Ground fault. After machine initialization following load flow estimations, these faults are initiated respectively at 0.1 sec. and cleared at 0.2 sec. rotor swing plot and power plot are simulated for three conditions; (a). When neither PSS, nor SVC is ON during fault. (b). When only PSS is ON. (c). When both PSS and SVC are ON.

2.4 Critical clearing time estimation using classical method

In estimating the critical clearing, time the following steps were followed;

i. The load flow solutions from simpowersystem configuration of the test system as in Fig. 2 are used for synchronous internal generated voltage.
ii. The values of V_t, P_t, and Q_t are obtained from the load flow solution in section 2.2 and are used to estimate the synchronous internal generated voltage.

$$I_g = (P_t - jQ_t)/V_t^2 \tag{4}$$

$$E_g = V_t + jX_d^{'}\mathrm{I_g} \tag{5}$$

Where I_g = Generator terminal Currrent, P_t = Scheduled real system power, jQ_t = Scheduled reactive system power, V_t = Generator terminal Voltage, E_g = Transient emf of generator and $jX_d^{/}$ = Transient reactance.

2.5 Transfer impedance for transient stability studies

The transfer impedances of various faults are estimated and these depend on the position of fault and the fault impedance. In this test case, the fault impedance purely resistive and the fault position is at the generator bus and hence the transfer impedances are estimated by applying equation (6)

$$Z_T = \left| Z_a + Z_b + (Z_a Z_b)/(Z_c + Z_{fsh}) \right| \tag{6}$$

and the fault shunt for the different faults are as shown in Table I, while Table 2 shows calculated transfer impedance for different types of faults in this study.

Table I: Fault shunt for different types of faults

Types of faults	Fault shunt(Z_{fsh})
L-G	Z_2+Z_0
L-L	Z_2
L-L-G	Z_2Z_0 / (Z_2+Z_0)
L-L-L(G)	0

Table II: Calculated transfer impedance for different types of faults

L-G(pu)	L-L-G(pu	L-L-L-G(pu)
1.1083	1.501	1.036

2.6 Estimation of maximum electrical power developed by the machine

The maximum electrical power developed by the machine for various faults is estimated substituting the calculated transfer impedances in Table II in equation (7).

$$P_{e(\max)} = \frac{|E_g||V_t|}{Z_t} \tag{7}$$

Transfer impedance Z_t is calculated and shown in Table II.

2.7 Estimation of critical clearing time (CCT) using Runge Kutta.

When this calculated maximum electrical power is used with other variables as required by the Runge-kutta solution of the rotor swing equations (1) and (2), a simulation of the rotor swing response is obtained. The rotor swing response are shown in figs. 10 to 24, while the critical clearing time is read from these graph having calculated the critical clearing angle using equation (3). Compare critical clearing time result with that obtained through statistical pattern recognition in Table III.

Table III: Critical clearing time

H(sec)		24	15	12	7.4	5
Three phase to ground Fault	SPL(SVC NO) CCT	0.5985	0.4910	0.4467	0.3663	0.3142
	SPL(SVC ON) CCT	0.5995	0.4953	0.4516	0.3705	0.3181
	% CCT time gain by SVC	-0.1671	-0.8758	-1.0969	-1.1466	-1.2412
	Classical CCT estimation	0.6308	0.4995	0.4460	0.3514	0.2888
	Classical CCT error	-5.3968	-1.7312	0.1567	4.0677	8.0840
Double phase to ground Fault	SPL(SVC NO) CCT	0.8545	0.6842	0.6124	0.4897	0.4094
	SPL(SVC ON) CCT	0.8600	0.6905	0.6205	0.4952	0.4132
	% CCT time gain by SVC	-0.6437	-0.9208	-1.3227	-1.1231	-0.9282
	Classical CCT estimation	0.8754	0.6921	0.6194	0.4862	0.4000
	Classical CCT error	-2.4459	-1.1546	-1.1430	0.7147	2.2960
Single phase to ground Fault	SPL(SVC NO) CCT	2.115	1.556	1.427	1.001	0.832
	SPL(SVC ON) CCT	—	—	—	—	—
	% CCT time gain by SVC	—	—	—	—	—
	Classical CCT estimation	1.89	1.494	1.336	1.049	0.8625
	Classical CCT error	10.6383	3.9846	6.3770	-4.7952	-3.6659

III. RESULTS AND DISCUSSION

Figures 3 – 5 show plots of rotor angle versus time for single line, double line to ground and three-phase faults respectively. The plots show various transient responses for non presence of PSS and SVC, presence of PSS and no SVC and finally the presence of both PSS and SVC.

Figures 6 – 9 show simulation results plots of only three-phase rotor angle – time response for SIME for different conditions at different clearing times.

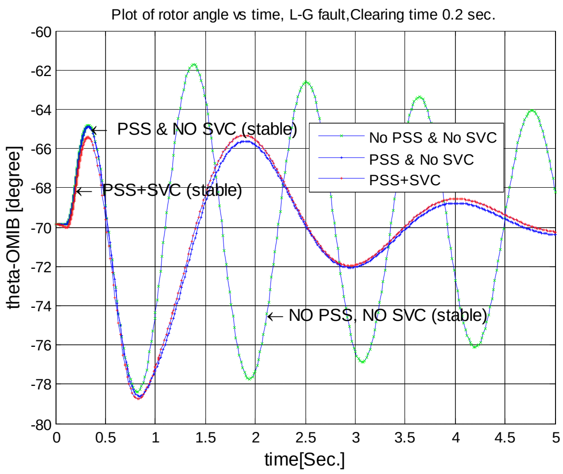

Figure 3: plot of rotor angle versus time for single line to ground fault

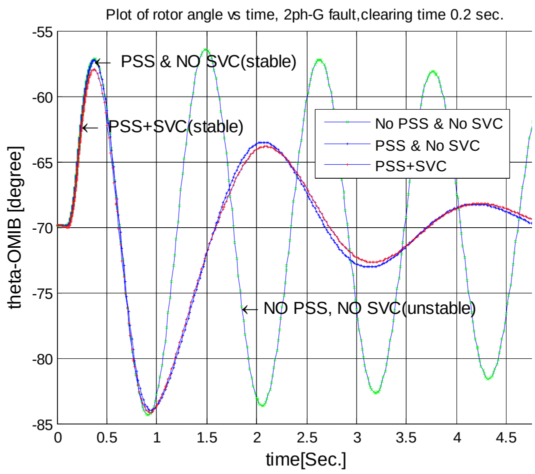

Figure 4: plot of rotor angle versus time for double phase to ground fault

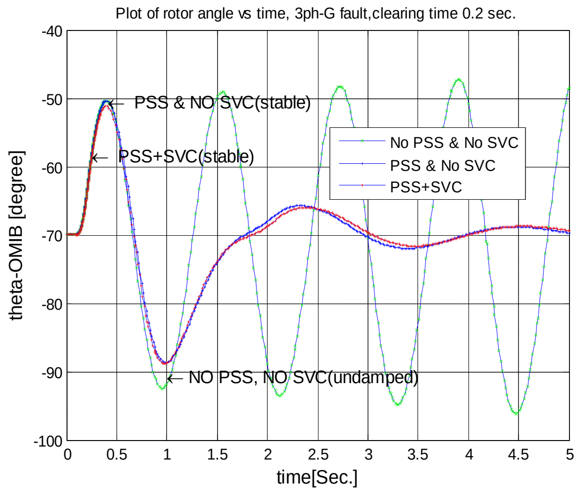

Figure 5: plot of rotor angle versus time for three phase to ground fault

Figure 6: 3Φ-G Rotor angle – time response for SIME, PSS & No SVC at clearing time of 0.36635 Sec

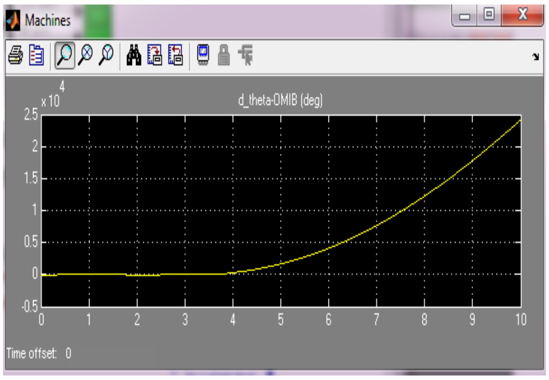

Figure 7: 3Φ-G Rotor angle – time response for SIME, PSS & No SVC at clearing time of 0.3664 Sec.

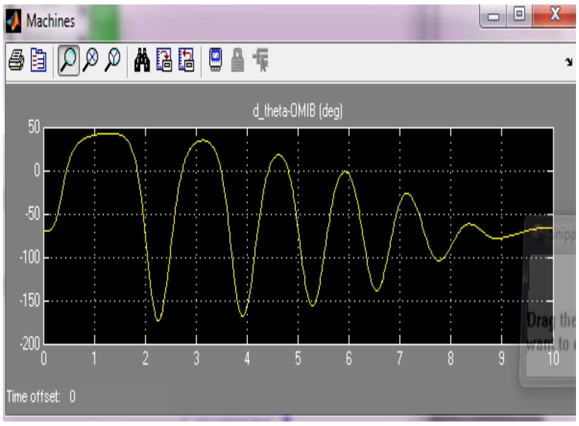

Figure 8: 3Φ-G Rotor angle – time response for SIME, PSS & SVC ON at clearing time of 0.3705 Sec.

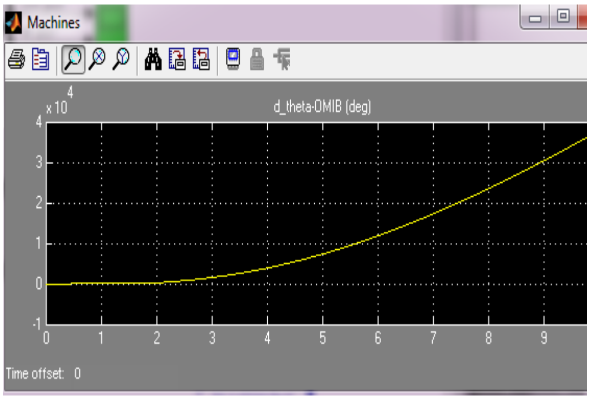

Figure 9: 3Φ-G Rotor angle – time response for SIME, PSS & SVC ON at clearing time of 0.3706 Sec.

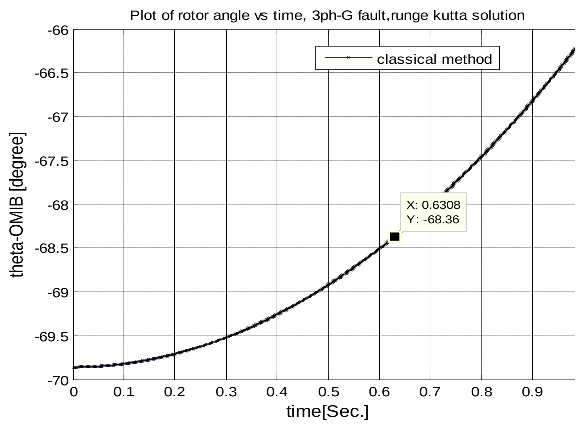

Figure 10: plot of rotor angle versus time (Runge-Kutta solution), 3Ph-G, H=24 sec.

Figures 10 – 24 show plots of rotor angle versus time as calculated using 4th Order Runge-Kutta solution at different inertia values and for various faults.

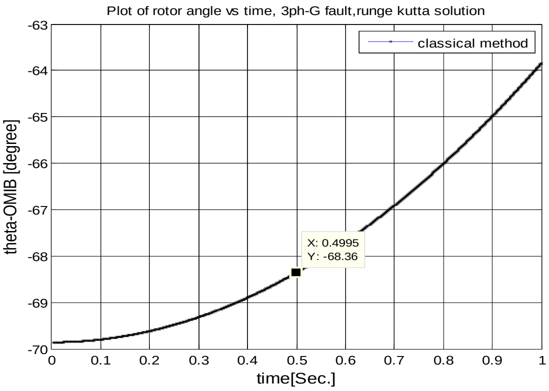

Figure 11: plot of rotor angle versus time (Runge-Kutta solution), 3Ph-G, H=15 sec

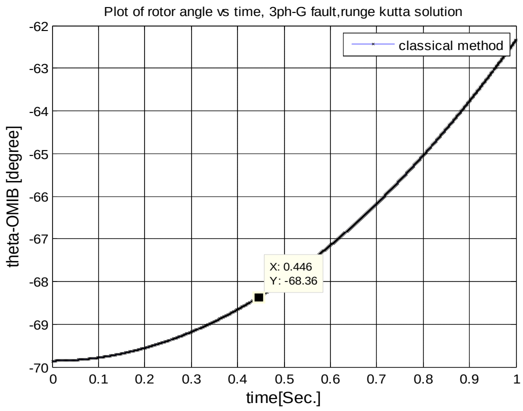

Figure 12: plot of rotor angle versus time (Runge-Kutta solution), 3Ph-G, H=12 sec

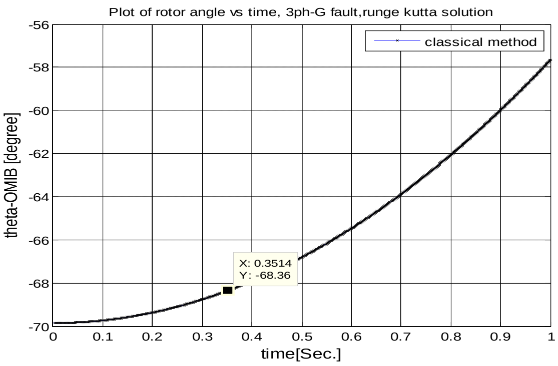

Figure 13: plot of rotor angle versus time (Runge-Kutta solution),3Ph-G, H=7.4 sec.

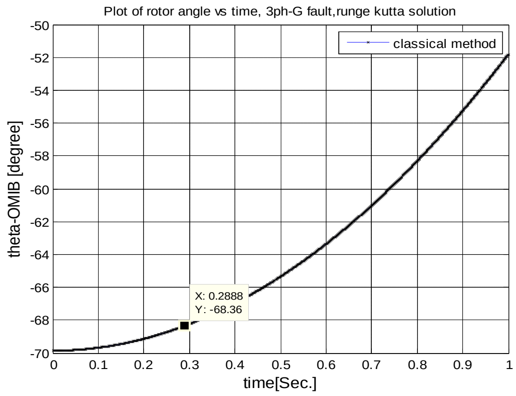

Figure 14: plot of rotor angle versus time (Runge-Kutta solution),3Ph-G, H=5.0 sec.

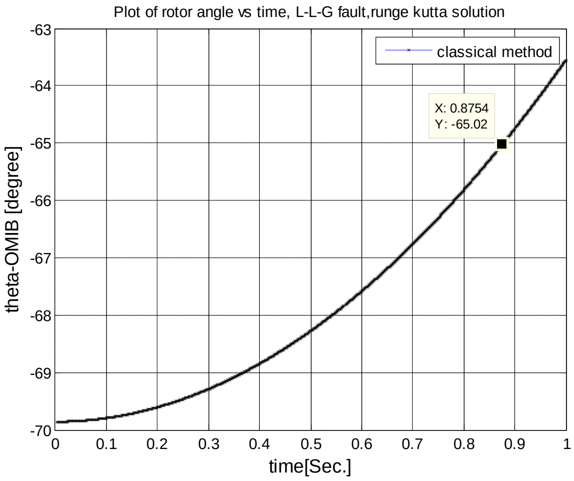

Figure 15: plot of rotor angle versus time (Runge-Kutta solution), L-L-G, H=24 sec

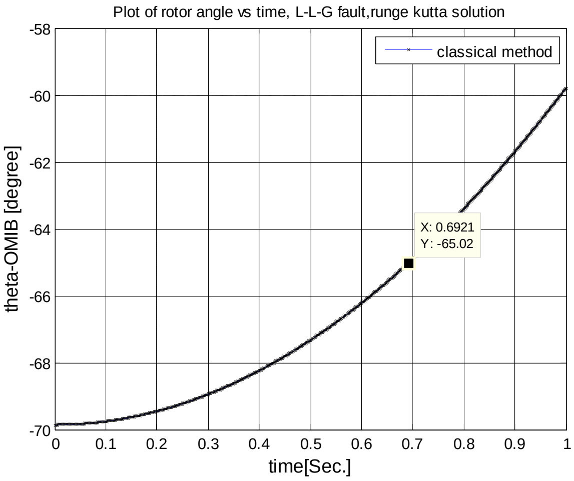

Figure 16: plot of rotor angle versus time (Runge-Kutta solution), L-L-G, H=15 sec

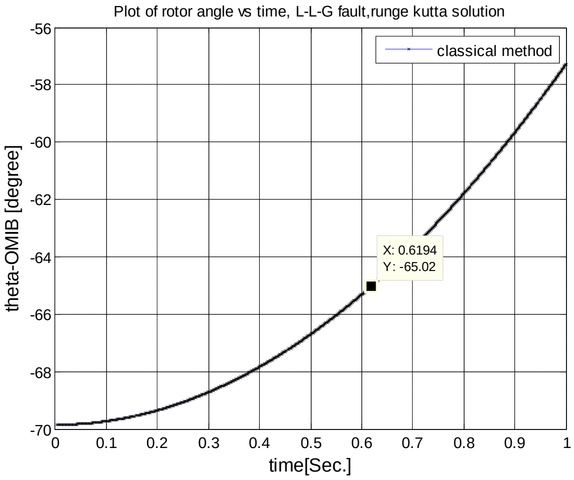

Figure 17: plot of rotor angle versus time (Runge-Kutta solution), L-LG, H=12 sec

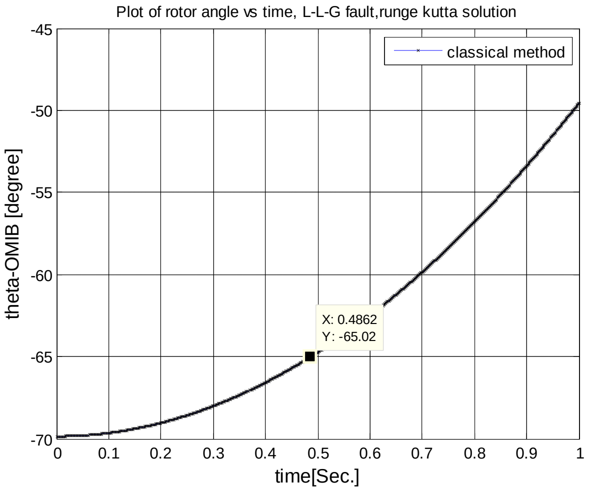

Figure 18: Plot of Rotor Angle versus Time (Runge-Kutta Solution), L-L-G, H=7.4 Sec

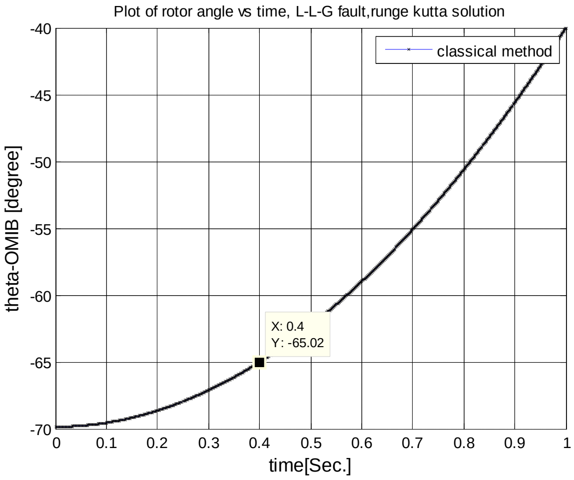

Figure 19: Plot of Rotor Angle Versus Time (Runge-Kutta Solution), L-L-G H=5.0 Sec

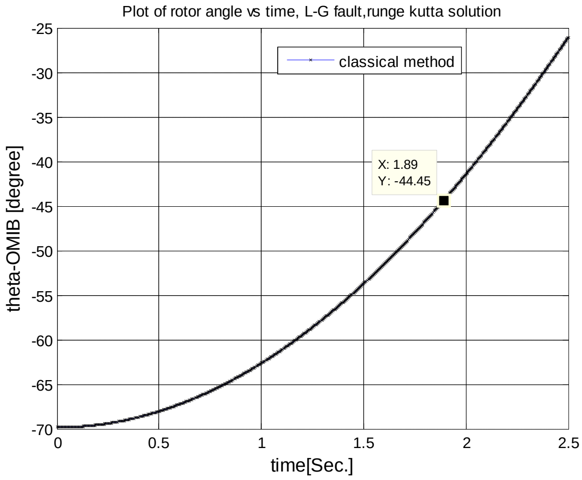

Figure 20: Plot Of Rotor Angle Versus Time (Runge-Kutta Solution), L-G, H=24 Sec

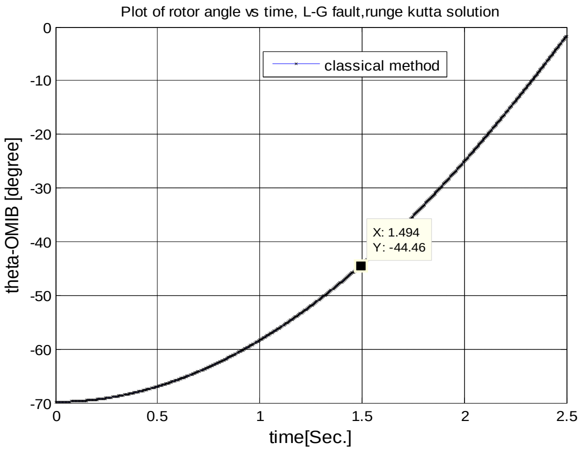

Figure 21: Plot Of Rotor Angle Versus Time (Runge-Kutta Solution), L-G, H=15 Sec

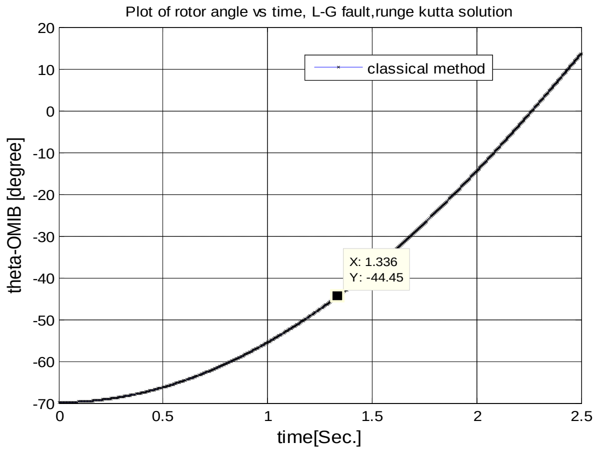

Figure 22: Plot Of Rotor Angle Versus Time (Runge-Kutta Solution), L-G, H=12 Sec

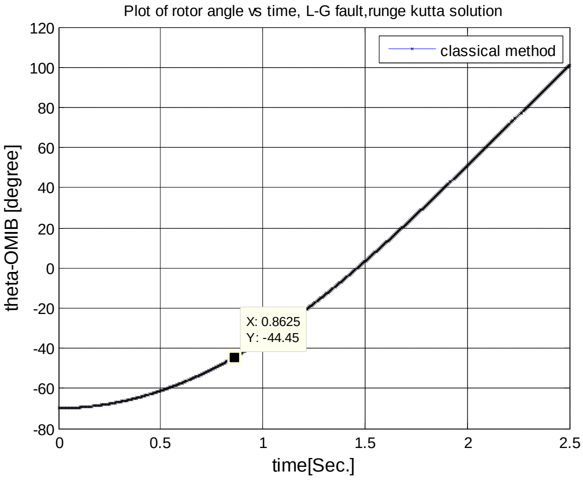

Figure 23: Plot Of Rotor Angle Versus Time (Runge-Kutta Solution), L-G, H=7.4 Sec

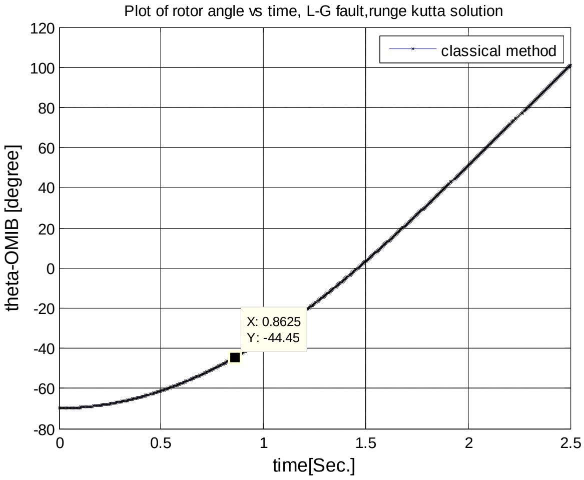

Figure 24: Plot Of Rotor Angle Versus Time (Runge-Kutta Solution), L-G, H=5.0 Sec

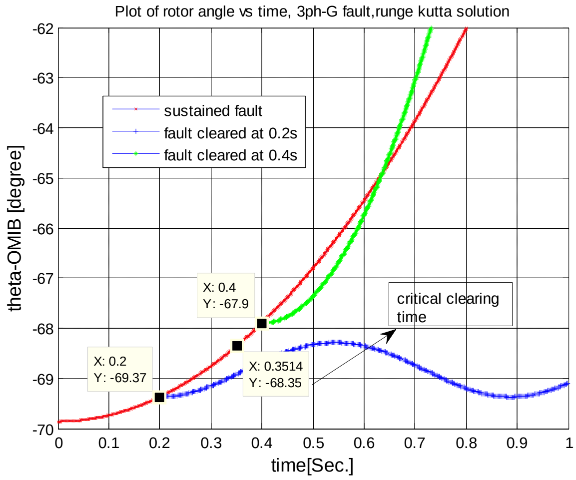

Figure 25: Comparison of Plot of Rotor Angle Versus Time (Runge-Kutta Solution), 3Ph-G, H=7.4 Sec

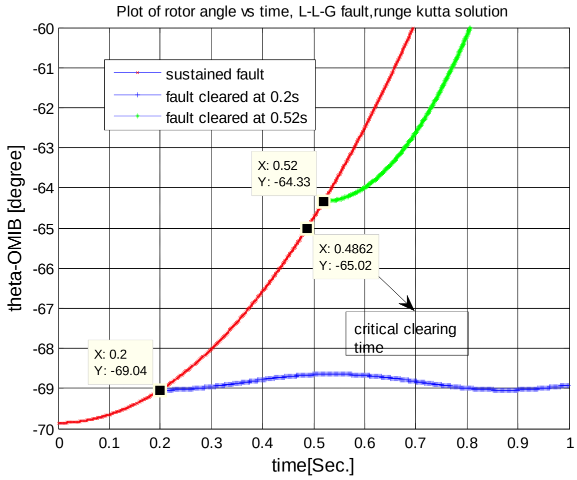

Figure 26: Comparison of Plot Of Rotor Angle Versus Time (Runge-Kutta Solution), L-L-G, H=7.4 Sec

Figure 25 shows comparison of plots of rotor angle versus time using Runge-Kutta 4th Order solution for three-phase to ground fault with inertia constant of 7.4 sec. for (i) Sustained fault, (ii) Fault cleared at 0.2s and (iii) Fault cleared at 0.4s showing Critical clearing time (CCT) of 0.3514sec.

Figure 26 show comparison of plots of rotor angle versus time using Runge-Kutta 4th Order solution for Double line to ground 7.4 sec. inertia constant for (i) Sustained fault, (ii) Fault cleared at 0.2s, and (iii) Fault cleared at 0.52sec with a Critical clearing time (CCT) of 0.4862secs.

IV. CONCLUSION

Transient stability analysis is a critical investigation in power system studies. This work evaluates essential parameters such as critical clearing time (CCT) from transient responses of different faults on a SIME connected to infinite busbar. The model was equipped with static variable compensator in the middle of the transmission line. This was the first stage of enhancement and the line was simulated with simpowersystem for three-phase fault, double line to ground fault and single line to ground fault to assist in drawing a good comparative analysis. . Also the classical model was used to compute the critical clearing time using equal area criteria with the fourth order Runge-Kutta numerical method. The simulation was done in MATLAB 7.5 environment.

In the fault analysis, different types of faults were introduced at the busbar and the faults were analyzed. The results show that during fault voltages and currents, the system is greatly affected by the three phase to ground fault as shown in Table III. Here the classical critical clearing time estimation for the three phase to ground fault was found to be 0.6308 sec followed by the classical critical clearing time for the double line to ground fault which was estimated to be 0.8754sec and lastly the single line to ground fault has its classical critical clearing time to be 1.89 sec. From the above extract, it becomes imperative to say that the three phase to ground fault is the most severe fault on the transmission system followed by the double line to ground fault. The least severe fault is the single line to ground fault.

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