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Critical Clearing Time Determination using Time Domain Method for Transient Stability Analysis of Synchronous Generator (SMIB)

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Abstract: Transient stability of synchronous generator can be analyzed by different methods like Time Domain Method, Direct Method , Approximation Method and Artificial Intelligence Method . This work aims at the analysis of transient stability analysis of synchronous generator in power system using time domain method.Problems and issues in these analyzed by time domain method was being identified . Advantages, disadvantages of time domain method was carried out through a simulation based on Critical Clearing Time (CCT) determination and necessary modelling for Single Machine Infinite Bus(SMIB) system.

Keywords: CCT (Critical Clearing Time), Transient stability analysis, Time domain method, SMIB (Single Machine Infinite Bus).

I. INTRODUCTION

Electrical Power system consists of generation, transmission and distribution and it is vulnerable towards different faults so, at the same time it should be reliable, stable and qualitative."Power system stability can be defined as the ability of a power system to remain in a state of operating equilibrium during normal conditions, and to regain an accepted state of operating equilibrium after a disturbance". [1][2]During Steady state conditions of the power systems, two main conditions needs to be satisfied for each generators: (1) Rotors speed should be in synchronize with system frequency. (2) The generated voltages should be sinusoidal waveforms with the same frequency. [4] These conditions get violated when any disturbances are developed on the power system. Due to these disturbances instability in rotor speed is developed. These disturbances may be small or large. Power system must be able to withstand against these disturbances. Power system stability can be classified as shown in figure-1.

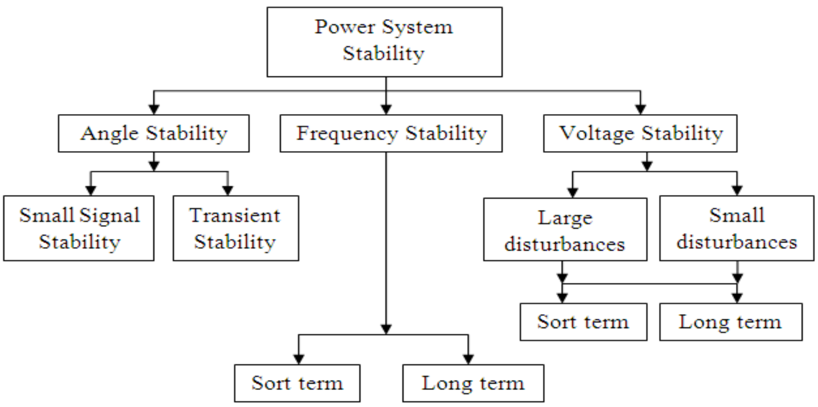

Figure 1.Types of power system stability phenomena Adapted from [Kundur and Morisson, 1997a]

The ability of a power system to recover and maintain synchronism is called rotor angle stability. [2] Small signal stability is the ability of the power system to maintain synchronism under small disturbances. [2] Transient stability is the ability of the power system to maintain synchronism under large disturbances. [2]

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II. CONCEPT OF TRANSIENT STABILITY

The rotor of synchronous generator is driven by prime mover. The frequency of the terminal voltage of the generator depends on the speed of rotor. Rotor mechanical speed is synchronized with the frequency of the stator electrical quantities.When two or more synchronous generators are inter connected, stator voltage and current of each generator must have the same frequency. The rotors of all interconnected generators must be in synchronism. During normal operating conditions of power system, Mechanical input power (Pm) from prime mover to generator shaft and generated electrical power (Pe) should be in balanced condition. When large disturbances (like a fault on the network, failure of equipments, sudden change in load, and loss of a line or generator) are developed on power system, the maintenance of rotor angle stability is known as transient stability. Due to these disturbances the synchronous machines may loss synchronism.For stability, the system oscillations must be damped, so that the inherent force in the system tends to reduce oscillations.

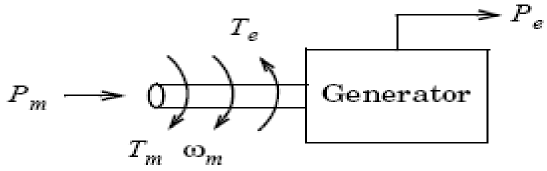

Figure-2: Generator-turbine torque balance

At normal operation,

$$\tau_m = \tau_e \Rightarrow p_m = p_e$$

If Large disturbance is developed on network, balance between mechanical torque and electrical torque is disturbed.

$$\tau_m > \tau_e \Rightarrow p_m > p_e$$

$$\tau_m < \tau_e \Rightarrow p_m < p_e$$

Rotor start to accelerate or decelerate. Due to these disturbances the synchronous machines may loss synchronism.hence swing equation came into existence.

III. SWING EQUATION

The swing equation shows the electro-mechanical oscillations in a power system. This equation provides the relative motion.

- Consider a synchronous generator with electromagnetic torque τ_e running at synchronous speed.
- During the normal operation, the mechanical torque, $\tau_m = \tau_e$
- A disturbance occurred will result in accelerating/decelerating torque.
- By the law of rotation,

$$J\frac{d^2\delta}{dt} = \tau_m - \tau_e$$

- If mechanical speed is multiplied both side,

$$J\omega_m\frac{d^2\delta}{dt} = p_m - p_e$$

- Swing equation in terms of inertial constant M

$$M\frac{d^2\delta}{dt} = p_m - p_e$$

$$\frac{2H}{\omega_0}\frac{d^2\delta}{dt} = p_m - p_e$$

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- If damping is considered then,

$$M\frac{d^2\delta}{dt} - D\frac{d\delta}{dt} = p_m - p_e$$

- If equation is converted into per unit values, $M = 2H/\omega_0$

$$\frac{2H}{\omega_0}\frac{d^2\delta}{dt} - D\frac{d\delta}{dt} = p_m - p_e \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots 1$$

- Electrical active power,

$$p_e = \frac{V_{1.}V_2}{X}\sin(\delta)$$

$$p_e = p_{e.max}\sin(\delta) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\ 2$$

- From (1) and (2),

$$\frac{2H}{\omega_0}\frac{d^2\delta}{dt} - D\frac{d\delta}{dt} = p_m - p_{e.max}\sin(\delta) \dots\dots\dots\dots\dots\dots.. \quad 3$$

Where, δ is the power angle
ω is the angular velocity(rad/s)
J is the total moment of inertia (kg.m^2)
M (=ωJ) is the moment of inertia
H is the inertia constant
D is is the damping coefficient

IV. LITERATURE REVIEW

This is a traditional method of transient stability analysis based on time-domain numerical integration. [3]

- A general overview of step by step numerical integration methods in time domain for power system stability analysis appears in Stott (1979). Several production grade time domain simulation packages described in the literature can be found, for example, in Electric Power Research Institute (1992), Kurita et al. (1993), de Mello et al. (1992), Stubbe et al. (1989) , and Tanaka et al. (1994). [15]
- Important conclusions and decisions are made based on the results of stability studies, Therefore the results of stability studies are as timely and accurate as possible.[6]
- The stability of the post fault system is assessed based on simulated post fault trajectories. The typical simulation period for the post fault system is 10 to 15 second.

System simulation takes 10 to 20 second. [15]

- In time domain method, detail modelling is required of the whole components of the power system.

V. TIME DOMAIN METHOD

- At present, stability analysis programs are based on step by step numerical integrations.
- Modelling of each components is required in this method.
- Modelling components:
  - Synchronous generator modelling
  - Excitation system modelling
  - Transformer and transmission line modelling
  - Different types of load modelling
  - Facts controller modelling
  - Turbine and speed control scheme modelling
- Different type of models is possible in case of synchronous generator.
  - Model 0.0 (Classical model)
  - Model 1.0 (Only field circuit)
  - Model 1.1 (One field circuit on d-axis and one damper circuit on q-axis)
  - Model 2.1 (One field and one damper circuit on d axis, one damper on q-axis)
  - Model 2.2 (Two circuit on d-axis and two circuit on q-axis)
  - Model 3.2 (Three circuit on d-axis and two circuit on q-axis)
  - Model 3.3 (Three circuit on d-axis and three circuit on q-axis)

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- Mostly 1.1 and 2.1 model is used in practice.

VI. SYNCHRONOUS GENERATOR MODELLING (2.1 MODEL)

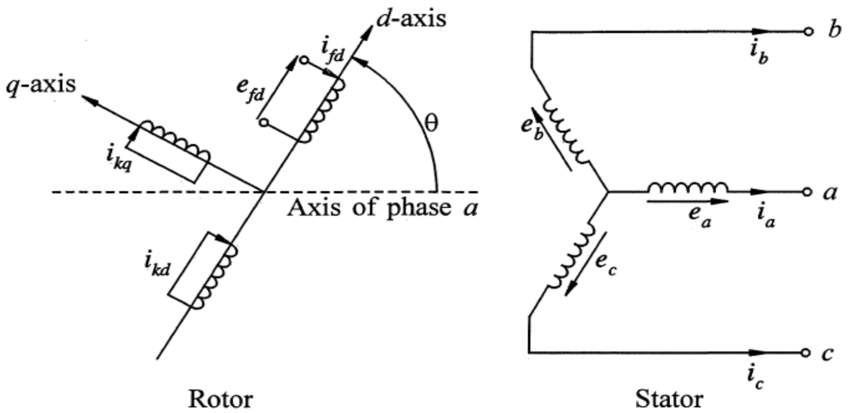

Figure-5: Synchronous generator stator rotor circuits

- Steps for modelling:
- Forming mathematical equations from circuit in abc form.
- Park's transformation is used to change time variant quantities into time invariant quantities and forming mathematical equations in dq0 form.
- Forming MATLAB Model from mathematical equation

Step-1: Forming Mathematical Equations

- Equations in abc form from circuits,

$$v_s = -\frac{d\psi_s}{dt} - [R_s]i_s \quad \ldots\ldots(1)$$

$$v_r = -\frac{d\psi_r}{dt} - [R_r]i_r \quad \ldots\ldots(2)$$

$$v^t{}_s = [v_a \quad v_b \quad v_c]$$

$$v^t{}_s = [v_f \quad 0 \quad 0 \quad 0]$$

- Relation between flux and current,

$$\psi = [L]i \quad \ldots\ldots(3)$$

Inductance matrix in abc form, $[L] = \begin{bmatrix} L_{ss} & L_{sr} \\ L_{rs} & L_{rr} \end{bmatrix}$

Step-2: Park's transformation

$$f_{abc} = [C_p]f_{dq0} \quad \ldots\ldots(4)$$

$$f_{dq0} = [C_p]^{-1}f_{abc} \quad \ldots\ldots(5)$$

Where,

$$[C_p] = \sqrt{\frac{2}{3}}\begin{bmatrix} \cos\theta & \sin\theta & \frac{1}{\sqrt{2}} \\ \cos\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta - \frac{2\pi}{3}\right) & \frac{1}{\sqrt{2}} \\ \cos\left(\theta + \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) & \frac{1}{\sqrt{2}} \end{bmatrix}$$

Voltage equations in dq0 form after applying park's transformation,

$$v_d = -\frac{d\psi_d}{dt} - \omega\psi_q - R_a i_d \quad \ldots\ldots(i)$$

$$v_q = -\frac{d\psi_d}{dt} + \omega\psi_d - R_a i_q \quad \ldots\ldots(ii)$$

$$v_0 = -\frac{d\psi_0}{dt} + R_a i_0 \quad \ldots\ldots(iii)$$

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$$v_f = \frac{d\psi_f}{dt} + R_f i_f \ldots\ldots (iv)$$

$$0 = \frac{d\psi_h}{dt} + R_h i_h \ldots\ldots (v)$$

$$0 = \frac{d\psi_g}{dt} + R_g i_g \ldots\ldots (vi)$$

Flux equations in dq0 form after applying park's transformation,

$$\psi_d = -L_{ls} i_d + L_{md}(-i_d + i_f + i_h) \ldots\ldots (vii)$$

$$\psi_q = -L_{ls} i_q + L_{md}(-i_q + i_g) \ldots\ldots (viii)$$

$$\psi_0 = -L_{ls} i_0 \ldots\ldots (ix)$$

$$\psi_f = -L_{lf} i_f + L_{md}(-i_d + i_f + i_h) \ldots\ldots (x)$$

$$\psi_h = -L_{lh} i_h + L_{md}(-i_d + i_f + i_h) \ldots\ldots (xi)$$

$$\psi_g = -L_{lg} i_g + L_{md}(-i_q + i_g) \ldots\ldots (xii)$$

Step-3: Forming MATLAB Model from mathematic equation

Using mathematical equations, MATLAB model can be prepared which can be used in time domain method for transient stability analysis.

Synchronous generator (2.1 Model) in MATLAB

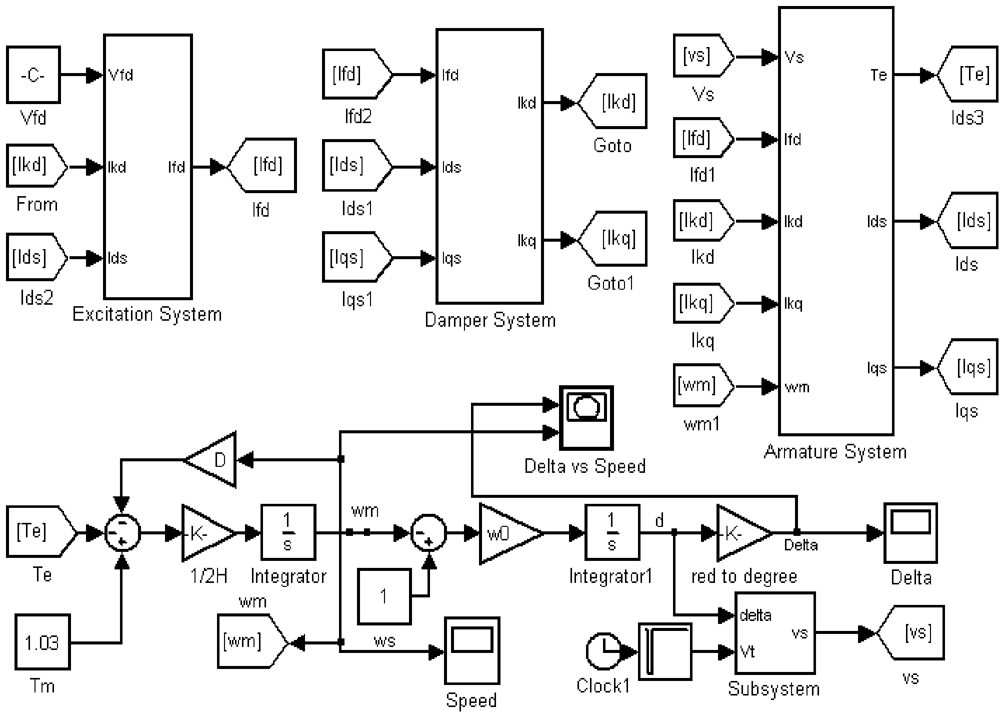
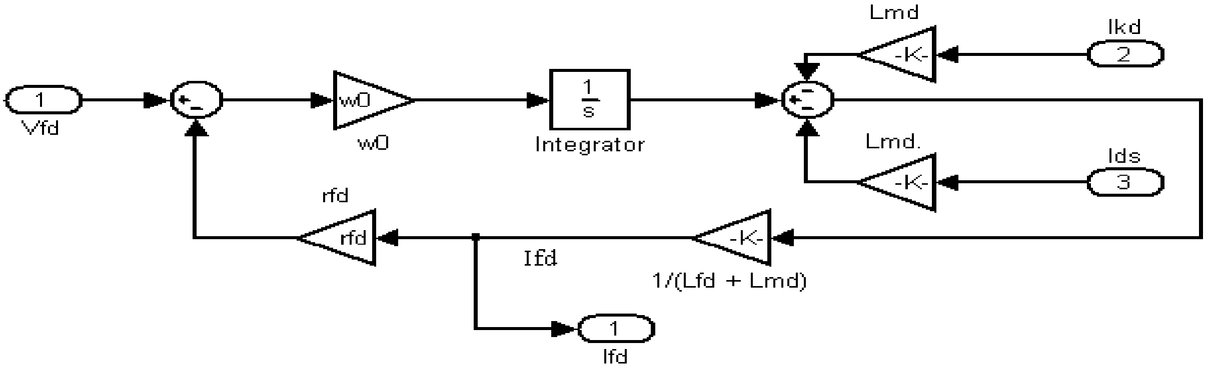


Figure-6: Synchronous generator 2.1 model

Field Circuit Model



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Damper Circuit Model

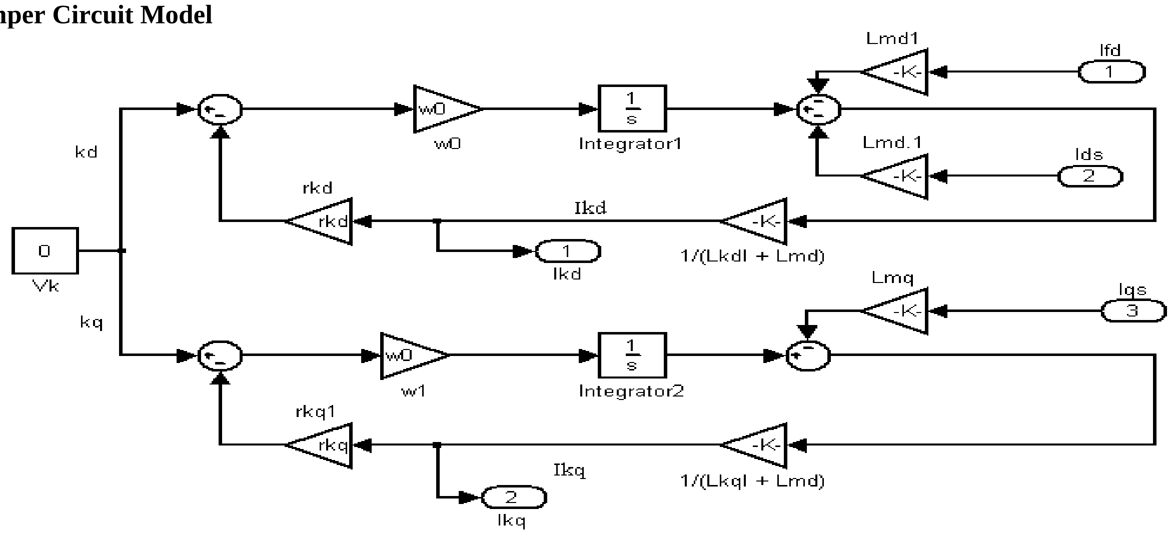

Figure-7.1: Field and Damper circuits model of 2.1 Synchronous Generator

Armature Circuit Model

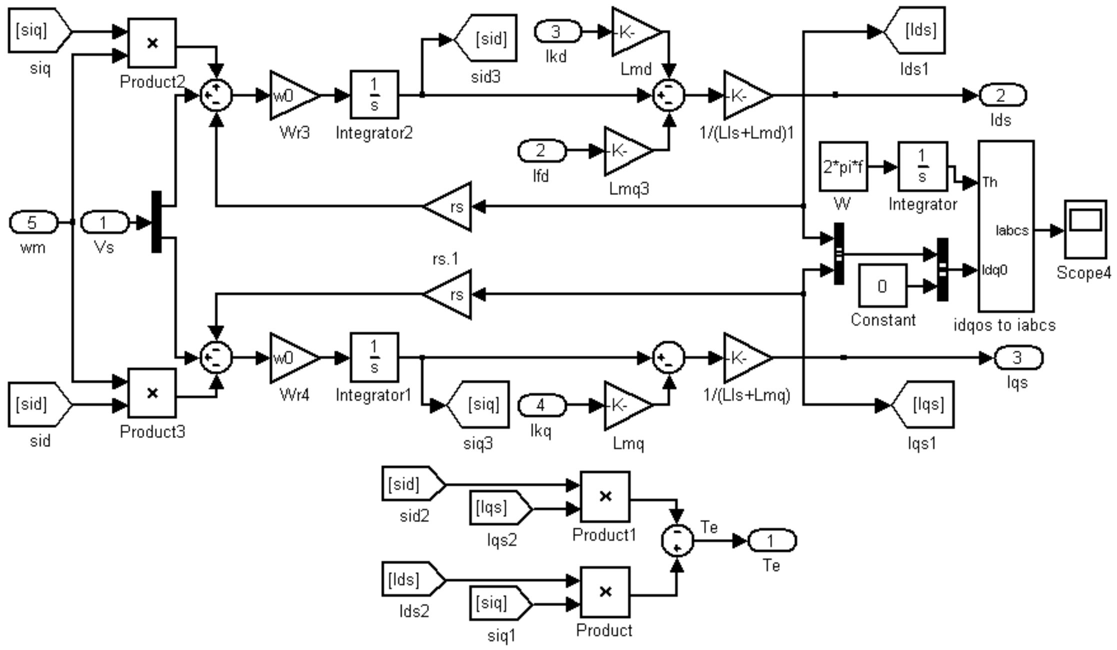

Figure-7.2: Armature Circuits model of 2.1 Synchronous generator

Three phase to ground fault is considered for above modelling.

Data used in transient stability analysis for synchronous generator[16]

Sr.No.	Generator Parameters	Value (pu)
1	Stator Resistance (rs)	0.02
2	d-axis inductance (Ld)	1
3	q-axis inductance (Lq)	1
4	Stator leakage inductance (Lal)	0.15
5	Field circuit resistance (rfd)	0.001
6	Field circuit inductance (Lfd)	0.2
7	d-axis damper circuit resistance (rkd)	0.02

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8	d-axis damper circuit inductance (Lkdl)	0.11
9	q-axis damper circuit resistance (rkq)	0.04
10	q-axis damper circuit inductance (Lkql)	0.15
11	Inertia constant (H)	4 sec
12	Damper coefficient (D)	1e-6
13	Frequency (f)	60
14	Terminal voltage (v)	1
15	Delivering current (Ia)	1.25
16	Power factor (pf)	0.8
17	Clearing time (tc)	0.35, 0.36 sec
18	Field Circuit voltage (vf)	0.00218

Lmd=Ld-Lal
Lmq=Lq-Lal

VII. SYNCHRONOUS GENERATOR MODELLING (0.0 CLASSICAL MODEL)

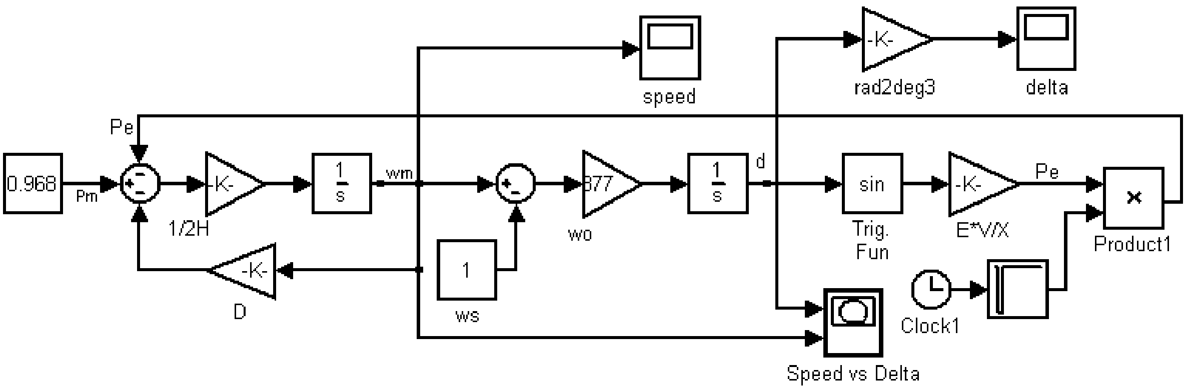
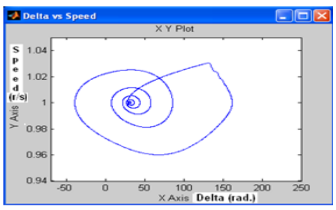
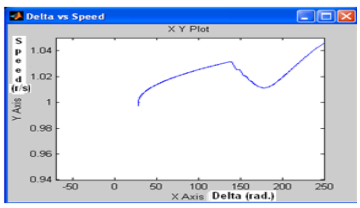
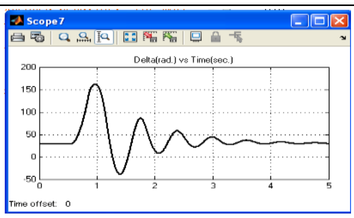
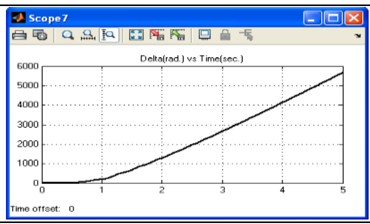


Figure-8: Classical Synchronous generator model

VIII. RESULT (2.1 MODEL)

Fault Clearing Time		
	0.35 second	0.36 second
DELTA(rad.) v/s SPEED(rad./sec)		
DELTA(rad.) v/s TIME(sec)		

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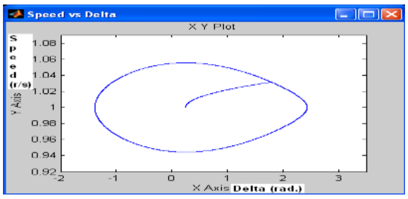
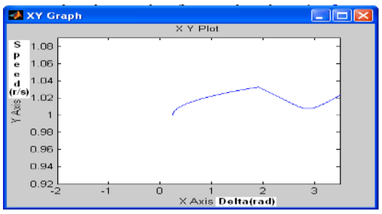
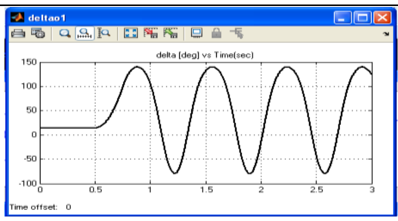
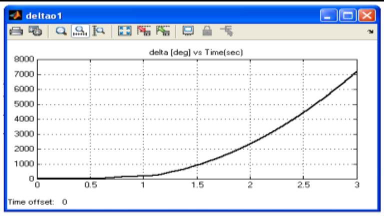
IX. RESULT (0.0 CLASSICAL MODEL)

Fault Clearing Time		
	0.26 second	0.27 second
DELTA(rad.) v/s SPEED(rad./sec)		
DELTA(rad.) v/s TIME(sec)		

X. CONCLUSION

In 2.1 synchronous generator model while considering 0.35 second as a fault clearing time our system is able to regain it's equilibrium steady state hence system is stable and getting damped oscillations which shows the presence of damper circuit . Our system is becoming unstable at 0.36 second and hence getting exponentially increasing response hence 0.35 second is considered to be critical clearing time. In 0.0 classical synchronous generator model while considering 0.26 second as a fault clearing time our system is able to regain it's equilibrium steady state hence system is stable and getting sustained oscillations which shows the absence of damper circuit. Our system is becoming unstable at 0.27 second and hence getting exponentially increasing response hence 0.26 second is considered to be critical clearing time. Here the CCT obtained by both the models have negligible difference also the value of CCT obtained during classical model is less; so if systems protective system is designed with CCT of classical model then in practical condition our power system will be fast responsive and more reliable.

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