ISLAMIC UNIVERSITY OF TECHNOLOGY (IUT)

THE ORGANIZATION OF ISLAMIC COOPERATION (OIC)

GAZIPUR-1704, DHAKA, BANGLADESH

OCTOBER- 2012

Thesis On:

SMALL SIGNAL STABILITY STUDY OF A GRID CONNECTED PHOTOVOLTAIC (PV) GENERATION STATION

Prepared By:

SHAKIR-UL HAQUE KHAN (082481)

MD. SHAHADAT HOSSAIN (082443)

MD. NAZIM UDDIN SUNNY (082453)

Supervised By:

ASHIK AHMED

Assistant Professor

Department Of Electrical And Electronic Engineering (EEE)

Islamic University Of Technology (IUT)

Boardbazar, Gazipur, Dhaka

SMALL SIGNAL STABILITY STUDY OF A GRID CONNECTED PHOTOVOLTAIC (PV) GENERATION STATION

A Thesis submitted in partial fulfillment of the requirement for Bachelor In Science Degree of Electrical And Electronics Engineering

By

SHAKIR-UL HAQUE KHAN (082481)

MD. SHAHADAT HOSSAIN (082443)

MD. NAZIM UDDIN SUNNY (082453)

Approved by
Ashik Ahmed

……………………………………
Ashik Ahmed
Project Supervisor
Assistant Professor
Dept. of Electrical & Electronic Engineering (EEE)

……………………………………
Dr. Md. ShahidUllah
Head of the department
Electrical and Electronic Engineering (EEE)

Members:

……………………………………..…
SHAKIR-UL HAQUE KHAN (082481)

……………………………………..
MD. SHAHADAT HOSSAIN (082443)

……………………………………..
MD. NAZIM UDDIN SUNNY (082453)

Islamic University of Technology (IUT)
The Organization of the Islamic Cooperation (OIC)
Gazipur-1704, Dhaka, Bangladesh
October-2012

Acknowledgements

At first we would like to express our warm and utmost gratitude to our revered project supervisor, Ashik Ahmed ,Assistant professor in Islamic Technology Of Technology (IUT) who was there for us every step of the way .His invaluable guidance, extensive knowledge and deep insights are what made this achievement possible. Without his regular supervision and his vast patience we would still be at the drawing board. May Allah bless you for all times to come, Sir.

We would also like to express our love and thanks to our parents whose support and love have guided us through most of our life and still remains our inspiration to move forward. Everything we achieve is for their sake and hopefully we will never lose track of that in future.

ABSTRACT:

This study focuses on the effect of a grid connected Photovoltaic (PV) generating station on the power system small signal stability. Firstly a working model of the hybrid system was established using Parks reference frame of a synchronous machine. The model designed is that of a single machine infinite bus system connected to a PV generating station. Then through simulation and analysis, effects of the PV generating station on the power system local mode oscillation are observed. Thus the adverse effects on the power system small signal stability due to a gird-connected generating station is shown through some calculations of the critical operating condition .The linear(Eigen value) and non -linear simulations performed on the system model was used to confirm these observations. Finally some controllers are added to our system model in an attempt to minimize the effect of disturbance, the simulation results are noted and some conclusions are drawn.

Keywords: *Photovoltaics (PV), Small Signal Stability, Critical Operating Condition, Simulation, Controller*

Table Of Contents

List Of Figures

Page no

Chapter 1

INTRODUCTION

1.1 The Context

Solar energy has become one of the primary contenders to fulfill the world's need for sustainable energy sources for development in the 21^{st} century. The fact that it is clean, efficient and uses a fuel (sunlight) that is essentially free has done wonders for its popularity.

Traditionally generation of electricity involves the combustion of fossil fuels such as natural gas, coal and oil. The thermal energy from burning of fossil fuels is used either to directly rotate a turbine or to generate steam in a boiler which in turn moves the turbine .The turbine is coupled to a generator rotor which thus generates electricity. However this method of generation is largely dependent on the availability of fuels which a non-renewable resource and in many countries its reserves are being depleted at an alarming rate. Moreover, burning of fossil fuels releases a lot of flues gases like Carbon Dioxide, CO, Sulphur Dioxide, etc. These gases cause health hazards namely acid rain and even contribute to global warming. Moreover

Nuclear fuel despite its numerous attractive attributes as a fuel for power generation has many severe shortcomings. Nuclear fuels like uranium (U234) is very rare, expensive and requires extreme caution while handling. Dumping of nuclear wastes is also a major issue as dump sites are mostly rendered inhabitable. Construction of nuclear power stations is difficult, requires a lot of experience and requires the highest safety standards to be maintained to avoid disasters. Even with the most advanced safety and security measures in place, the possibility still exists that unpleasant situations will occur considering the recent nuclear disaster in Fukushima, Japan.

Current technological schemes for generating power, using solar energy includes Solar Photovoltaic (thin film technology, solar PV modules) and Concentrating Solar Power Technology (Sterling Dish, Parabolic Trough, Solar Power Tower, Fresnel Reflectors).Among them Solar photovoltaic technology can be used both for small and large scale power generation while CSP technology is used mostly in large scale power stations.

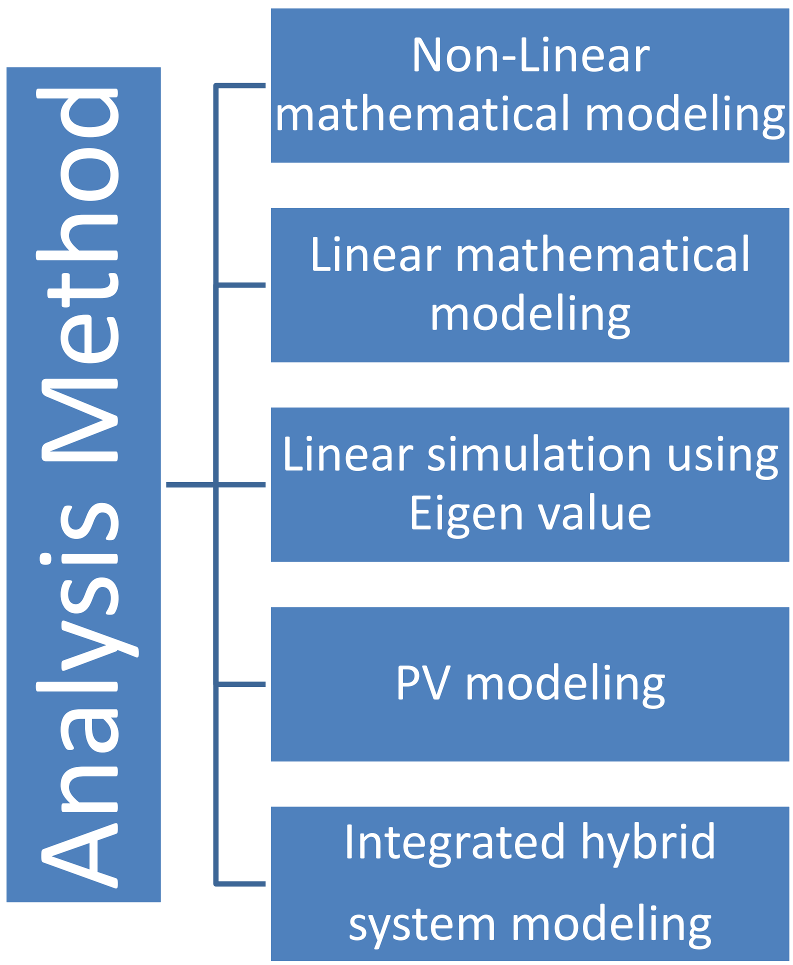
1.2 The Problem

However generation of power is one thing and integrating that power to the main grid of the power system is wholly another matter since integrating different types of generating stations to the system might result in some undesirable phenomenon.

Power system stability has always been of great concern in power system operation, since any disturbance in the system will hamper its synchronous mode of operation. The stability of system determines whether a system can settle down to a new or original steady state after the transients disappear. Of the two types of stability, small signal and transient stability, the former is the most frequently affected since generally it depends upon the system loading. Small signal stability are affected by the power system local mode oscillations which in turn are inherent from the rotor inertia. Our purpose is to investigate the damping of the local mode oscillations in a power system when it is penetrated by a PV generating station.

1.3 The Structure Of The Thesis

To identify and analyze the effects, the extensive model used is that of a single machine infinite bus system model without connecting the PV station. Rotor and Stator equations are developed using the Park's Reference Frame. Using these equations the generator initial conditions are derived which was then used to analyze, the effects of adding disturbance to the system. The effects of disturbance on the Heffron-Phillips constant were also observed. Then the PV station is connected to the single machine infinite bus system and appropriate equations are developed for the overall system to be analyzed. Calculation of the critical operating condition is done and its effect on rotor angle and other parameters are noted. That small signal stability is indeed affected by the PV station is reinforced using both linear and non-linear simulations of the overall system consisting of the conventional generating system and the PV station. Finally some controllers are connected to the system in an attempt of to reduce the power system oscillations and the after effects are noted.



Chapter 2

Modeling The Hybrid Generation System

2.1 Model:

The model of the single machine infinite bus system :

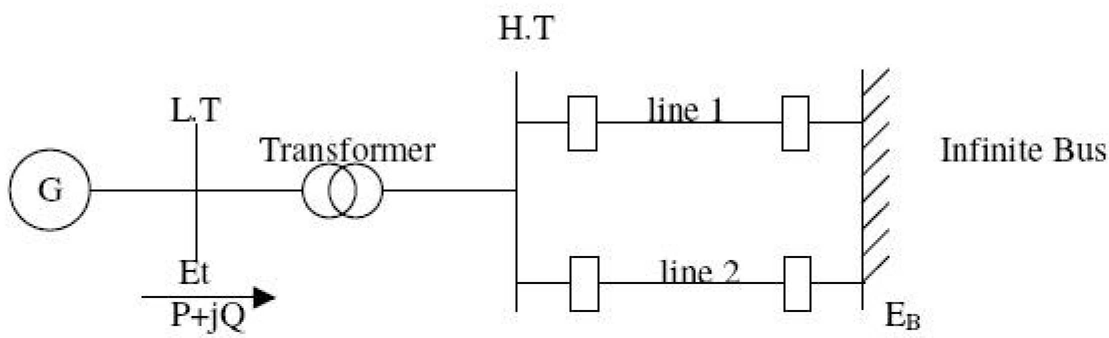


Fig 1. Single Machine Infinite Bus System

Consider a single machine system shown in Fig. 1. For simplicity, we will assume a synchronous machine represented by this model neglecting damper windings both in the d and q axes. (It is possible to approximate the effects of damper windings by a nonlinear damping term, if necessary). Also, thearma-ture resistance of the machine is neglected and the excitation system represented by a single time-constant system.

The algebraic equations of the stator are :

$$E_q' + x_d' = v_q \tag{1}$$

$$-x_{tsq} i_{tsq} = v_d \tag{2}$$

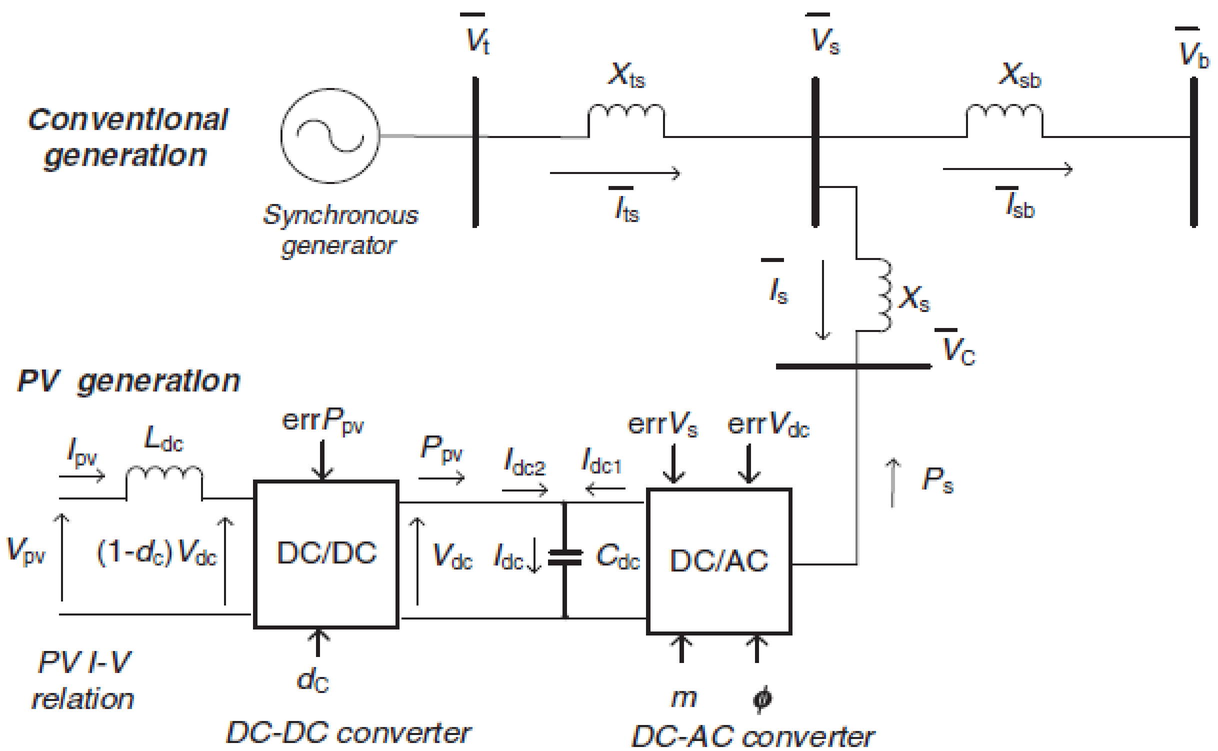


Fig 2. A power system integrated with a PV generation station.

2.2 Single Machine Infinite Bus System Integrated With A PV Generation Station

Figure 2 shows the configuration of a single-machine infinite-bus power system, where a PV power generation station is connected at bus bar denoted by letter ‘s’. Typical voltage–current characteristic of the PV generation is defined in Eq-(3).

$$V_{pv} = \frac{N_S nkT}{q} \ln\left(\frac{\frac{N_P I_{sc} I_r}{100} - I_{pv}}{N_P I_0} + 1 \right) \tag{3}$$

where T is the junction temperature, I_r the irradiance, Ns and Np the number of PV cells in series and parallel circuits, respectively, n the ideality factor, k the Boltzmann's constant, q the charge of electron, I_{sc} the short-circuit current and I_0 the saturation current. In figure-(1) results of substantial experiment have confirmed that the PV model of Equation (1) is suitable for the study of power system stability.

2.3 Network System Equations:

General mathematical model of a synchronous generator can be written as $\dot{X_g} = F(X_g, \overline{I_{ts}})$, where X_g is the variable vector of generator dynamics, and $\overline{I_{ts}}$ (or i_{tsd} and i_{tsq} expressed in d-q coordinate) is the generator output current. In this thesis, the following generator model is used, which is sufficient for the study of power system small-signal stability.

$$\dot{\delta} = \omega_0(\omega - 1)$$

$$\dot{\omega} = \frac{1}{M}[P_m - P_t - D(\omega - 1)] \quad (4)$$

$$\dot{E_q'} = \frac{1}{T_{d0}'}(-E_q + E_{fd})$$

$$E_{fd}' = TE(s)(V_{tref} - V_t)$$

Where for the simplicity of discussion, transfer function of the automatic voltage regulator is taken to be a first-order system TE(s) $= \frac{K_A}{1+sT_A}$ in this thesis and

$$P_t = E_q' i_{tsq} + (x_q - x_d') i_{tsd} i_{tsq}$$

$$E_q = E_q' - (x_d - x_d') i_{tsd} \quad (5)$$

$$V_t = \sqrt{V_{td}^2 + V_{tq}^2} = \sqrt{(x_q i_{tsq})^2 + (E_q' - x_d' i_{tsd})^2}$$

These are all the Mathematical model of the synchronous generator.

Considering the figure (2) the network equations are :

$$\overline{V_t} = jx_{ts}\overline{I_{ts}} + \overline{V_s}$$

$$\overline{V_s} = jx_s\overline{I_s} + \overline{V_c} \quad (6)$$

$$\overline{V_s} - \overline{V_b} = jx_{sb}(\overline{I_{ts}} - \overline{I_s})$$

From those equations we get,

$$j x_s \overline{I_s} + \overline{V_c} - \overline{V_b} = j x_{sb} (\overline{I_{ts}} - \overline{I_s})$$

$$\overline{V_t} = j x_{ts} \overline{I_{ts}} + j x_{sb} (\overline{I_{ts}} - \overline{I_s}) + \overline{V_b} \qquad (7)$$

In d-q coordinate, from above Equations, it can be obtained that

$$\begin{bmatrix} x_{sb} & -x_s - x_{sb} \\ x_q + x_{ts} + x_{sb} & -x_{sb} \end{bmatrix} \begin{bmatrix} i_{tsq} \\ i_{sq} \end{bmatrix} = \begin{bmatrix} -V_c \cos\varphi + V_b \sin\delta \\ V_b \sin\delta \end{bmatrix} \qquad (8)$$

$$\begin{bmatrix} x_{sb} & -x_s - x_{sb} \\ x'_d + x_{ts} + x_{sb} & -x_{sb} \end{bmatrix} \begin{bmatrix} i_{tsd} \\ i_{sd} \end{bmatrix} = \begin{bmatrix} V_c \sin\varphi - V_b \cos\delta \\ E'_q - V_b \cos\delta \end{bmatrix} \qquad (9)$$

The partial non-linear mathematical model of the power system of Figure 1 is thus established, the generator of Equations (4) and (5), and the integration of the generator and the PV power station with the power network of Equation (8-9).

2.4 System Linearized Model:

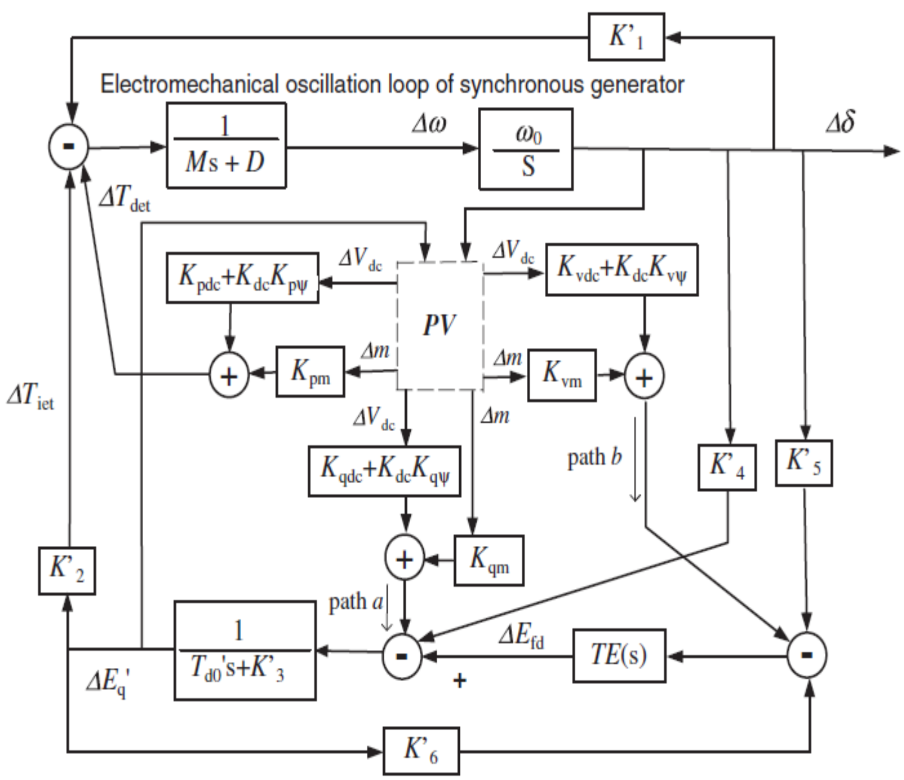


Fig 3: Linearized model of the part of PV integration with power system

The block diagram in Figure 3 describes the dynamics of the SMIB system along with PV connection. TheconstantsK'$_1$–K'$_6$in the block diagram describe the dynamic characteristic of the system known as the Heffron – Phillips K constants. K'$_1$ and K'$_2$are derived from the electric torque, while (K'$_3$ and K'$_4$) from the field winding circuit equations and (K'$_5$,K'$_6$) from the terminal voltage. The relating equations are indexed in Appendix A2.The constants K'$_2$,K'$_3$, K'$_4$ and K'$_6$ are usually positive and they affect the system differently. K'$_2$– K'$_4$ influence the electric torque in different manner depending on theoscillation frequency. When K_4 is positive, a positive damping torque component isintroduced. However, for negative value of K'$_4$, the damping will be negative.K'$_5$ on the other hand is commonly negative in practice. In the case where K_5 is positive, the AVR decreases the synchronizing torque and increases the damping torque. For negative values of K'$_5$, the AVR introduces a positive value of synchronizing torque and negative damping torque component.

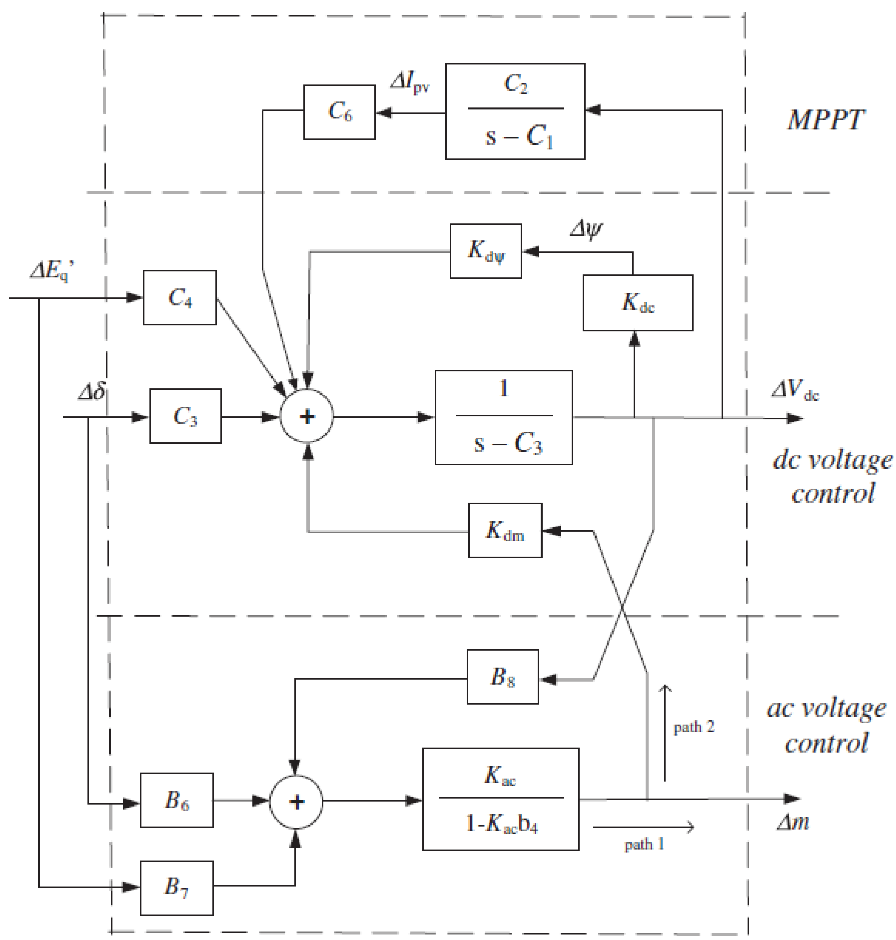


Fig 4 : Linearized model of the part of PV generation and Control where

$$
\begin{aligned}
C_0 &= km_0 \\
K_1' &= \left[E'_{q0} - i_{tsd0}\cdot\left(x_d' - x_q\right)\right](c_{11} + c_{12})V_b \cos\delta_0 - i_{tsq0}\cdot\left(x_d' - x_q\right)(d_{11} + d_{12})V_b \sin\delta_0 \\
K_2' &= i_{tsq0} - i_{tsq0}\cdot\left(x_d' - x_q\right)d_{12} \\
K_{pdc} &= -c_{11}C_0 \cos\psi_0\left[E'_{q0} - i_{tsd0}\cdot\left(x_d' - x_q\right)\right] - d_{11}C_0 \sin\psi_0 I_{tsq0}\cdot\left(x_d' - x_q\right) \\
K_{pm} &= -c_{11}V_{dc0}\cos\psi_0\left[E'_{q0} - i_{tsd0}\cdot\left(x_d' - x_q\right)\right] - d_{11}V_{dc0}\sin\psi_0 I_{tsq0}\cdot\left(x_d' - x_q\right) \\
K_{p\psi} &= c_{11}C_0 V_{dc0}\sin\psi_0\left[E'_{q0} - i_{tsd0}\cdot\left(x_d' - x_q\right)\right] - d_{11}C_0 V_{dc0}\cos\psi_0 I_{tsq0}\cdot\left(x_d' - x_q\right) \\
K_4' &= (d_{11} + d_{12})V_b \sin\delta_0(x_d - x_d') \\
K_3' &= d_{12}\left(x_d - x_d'\right) + 1 \\
K_{qdc} &= d_{11}C_0 \sin\psi_0\left(x_d - x_d'\right) \\
K_{qm} &= d_{11}V_{dc0}\sin\psi_0\left(x_d - x_d'\right) \\
K_{q\psi} &= d_{11}C_0 V_{dc0}\cos\psi_0\left(x_d - x_d'\right) \\
K_5' &= \frac{\left[v_{td0}v_q(c_{11} + c_{12})V_b\cos\delta_0 - V_{tq0}x_d'(d_{11} + d_{12})V_b\sin\delta_0\right]}{V_{t0}} \\
K_6' &= \frac{v_{tq0}\left(1 - x_d' d_{12}\right)}{V_{t0}} \\
K_{vdc} &= \frac{\left(-v_{td0}x_q c_{11}C_0\cos\psi_0 - v_{tq0}x_d' d_{11}C_0\sin\psi_0\right)}{V_{t0}} \\
K_{vm} &= \frac{\left(-v_{td0}x_q c_{11}V_{dc0}\cos\psi_0 - v_{tq0}x_d' d_{11}V_{dc0}\sin\psi_0\right)}{V_{t0}} \\
K_{v\psi} &= \frac{\left(v_{td0}x_q c_{11}C_0 V_{dc0}\sin\psi_0 - v_{tq0}x_d' d_{11}C_0 V_{dc0}\cos\psi_0\right)}{V_{t0}}
\end{aligned}
$$

Chapter 3

Variations Of Different Parameters Of The Single Machine Infinite Bus System without PV Station (With And Without Disturbance)

3.1 Variation Without Disturbance:

Case 1

Real Power=0.9p.u.

Reactive Power=-0.2p.u

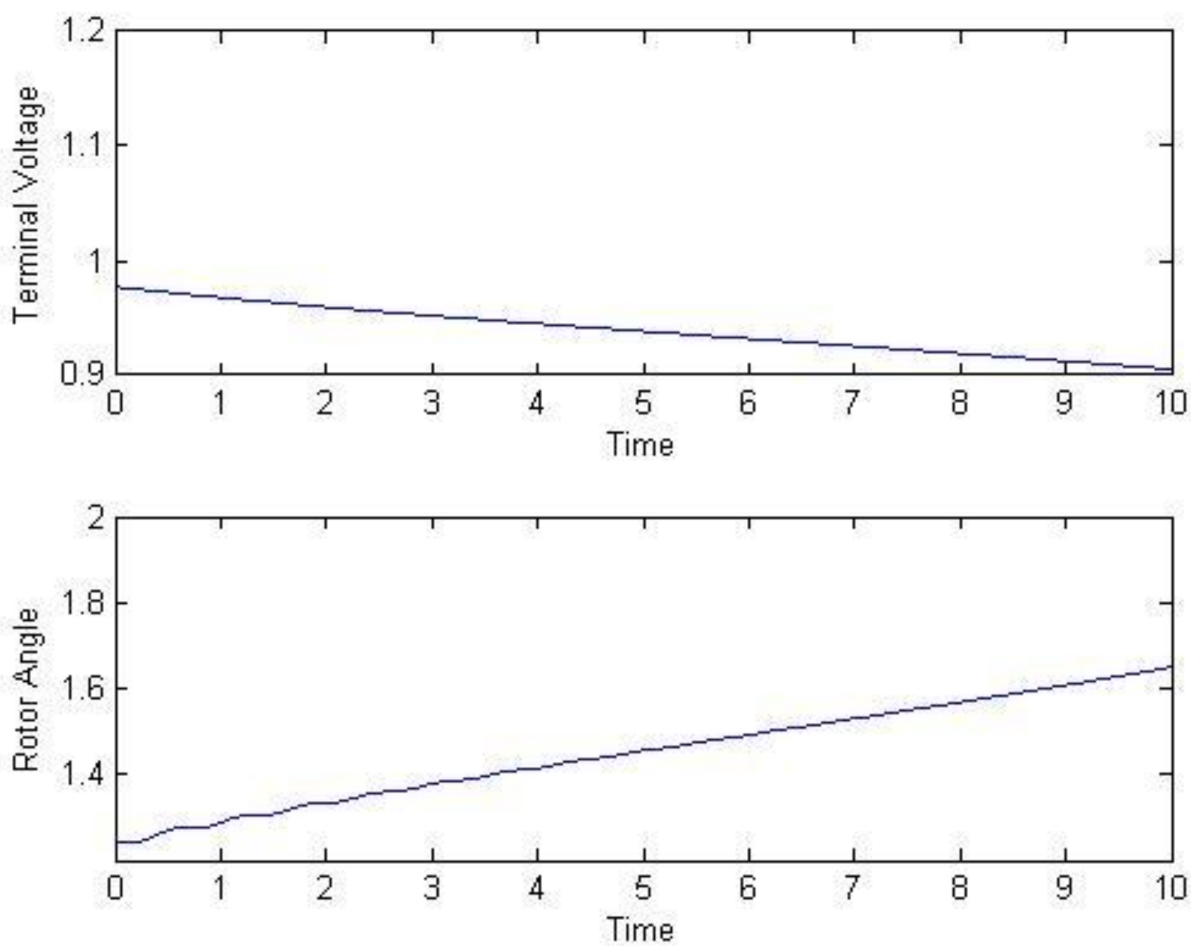


Fig 5**:** Variation Of Terminal Voltage & Rotor Angle with Time

Case 2:

Real Power=0.9 p.u

Reactive Power=-0.02p.u

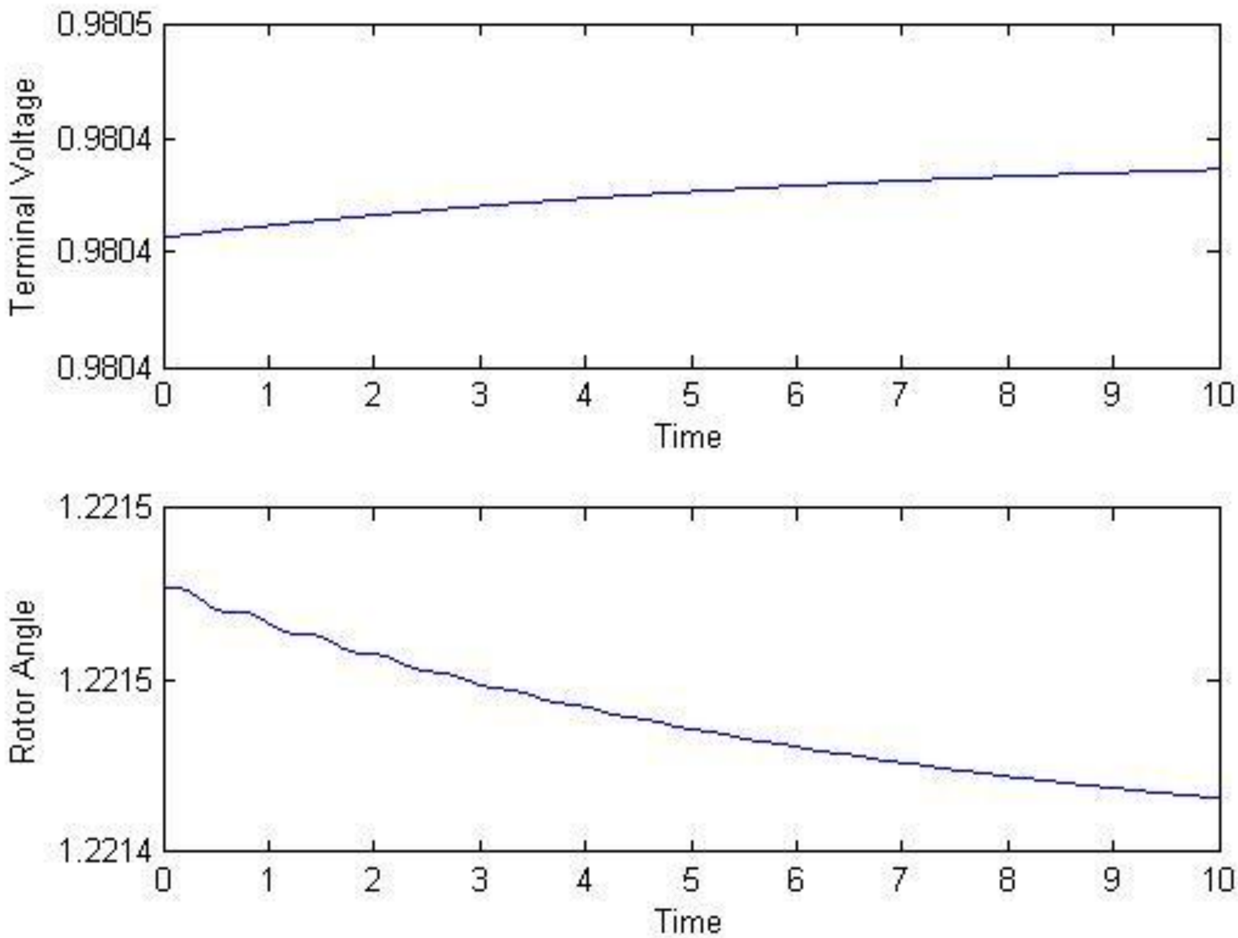


Fig 6**:** Variation Of Terminal Voltage & Rotor Angle with Time

Case 3:

Real Power= 0.3p.u

Reactive Power=0.02 p.u

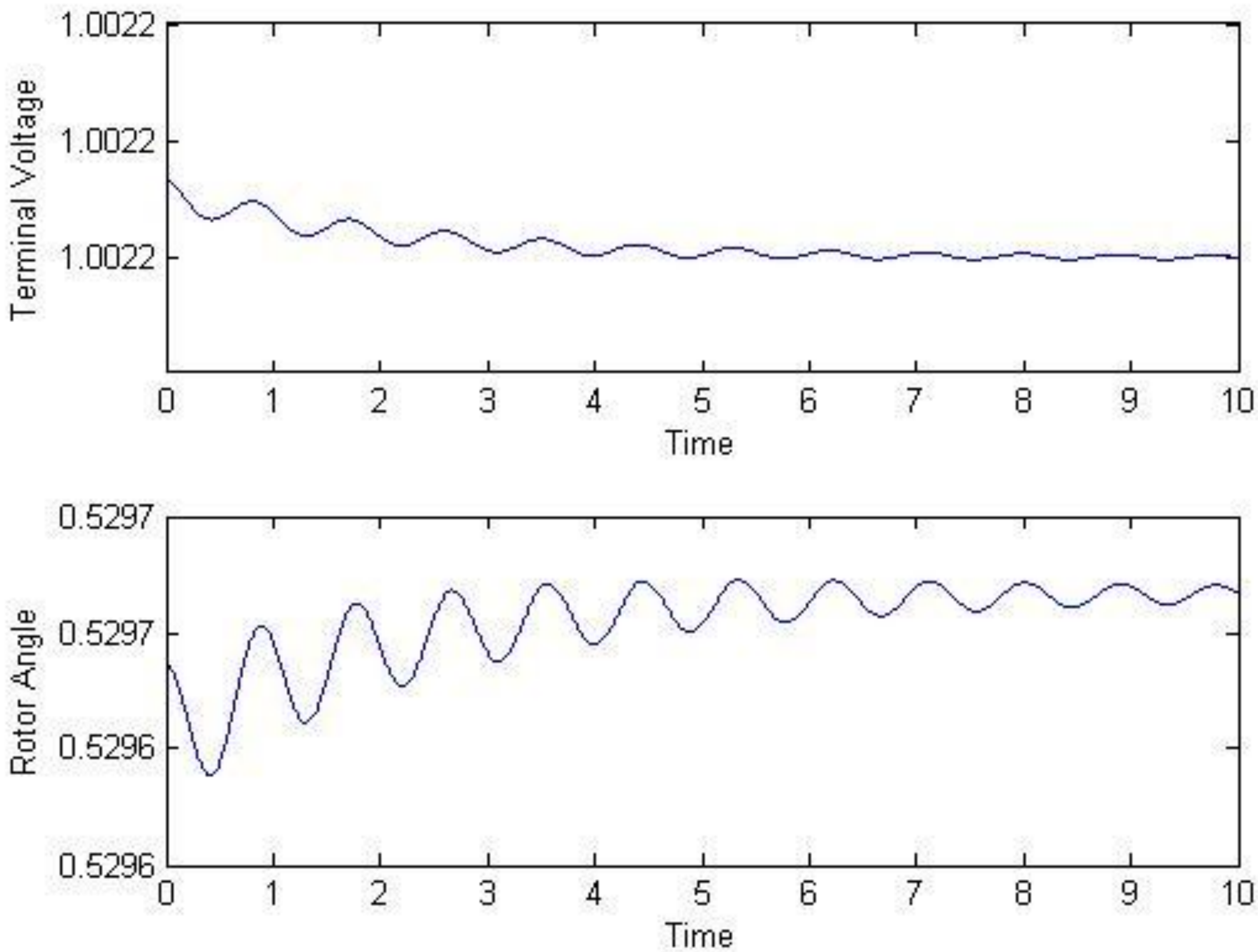


Fig 7 **:** Variation Of Terminal Voltage & Rotor Angle with Time

Case 4:

Real Power=0.3p.u
Reactive Power=-0.02p.u

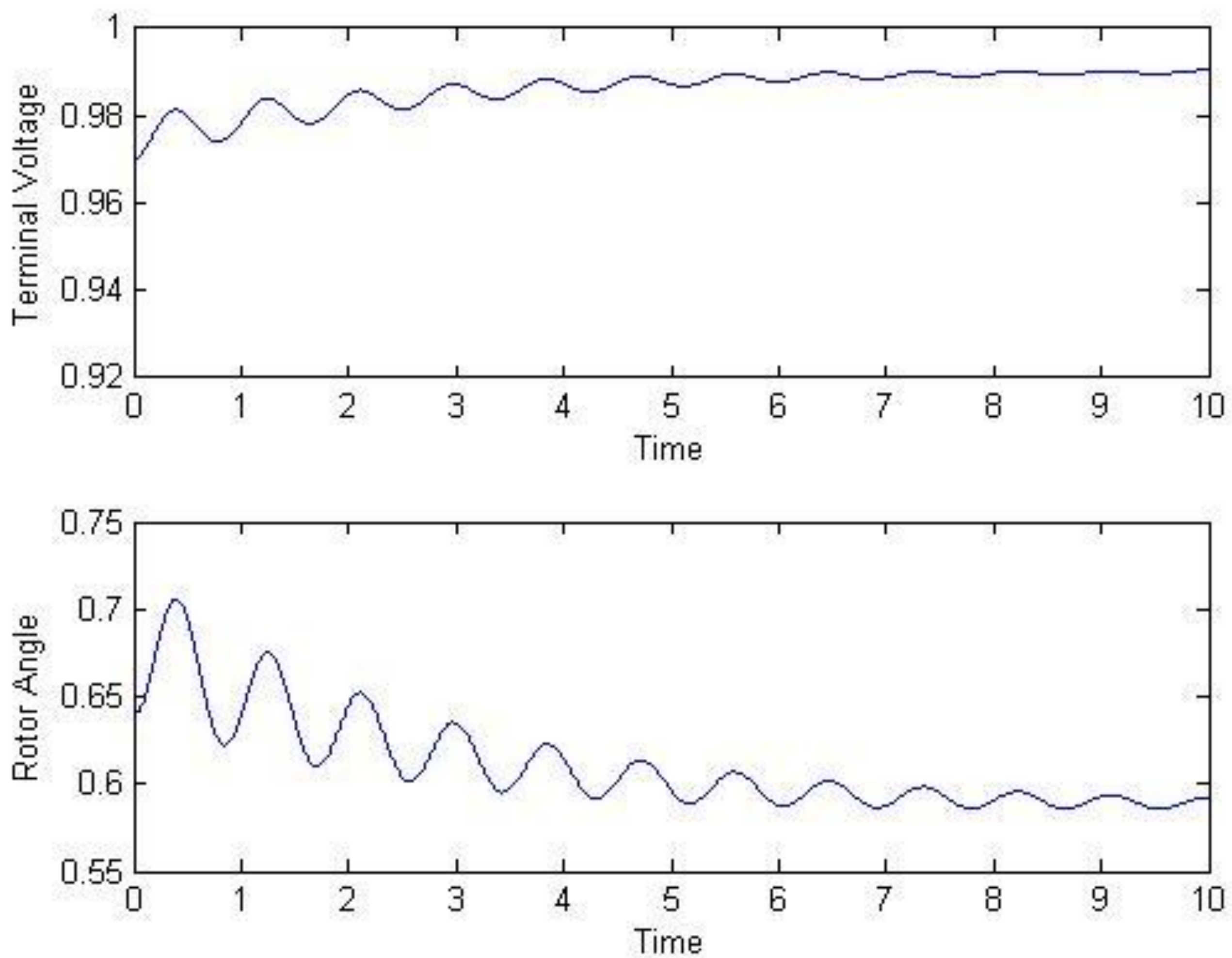


Fig 8: Variation Of Terminal Voltage & Rotor Angle with Time

3.2 Variation with Disturbance

Case 1

Real Power=0.9p.u.

Reactive Power=-0.2p.u

Disturbance at T= 1seconds

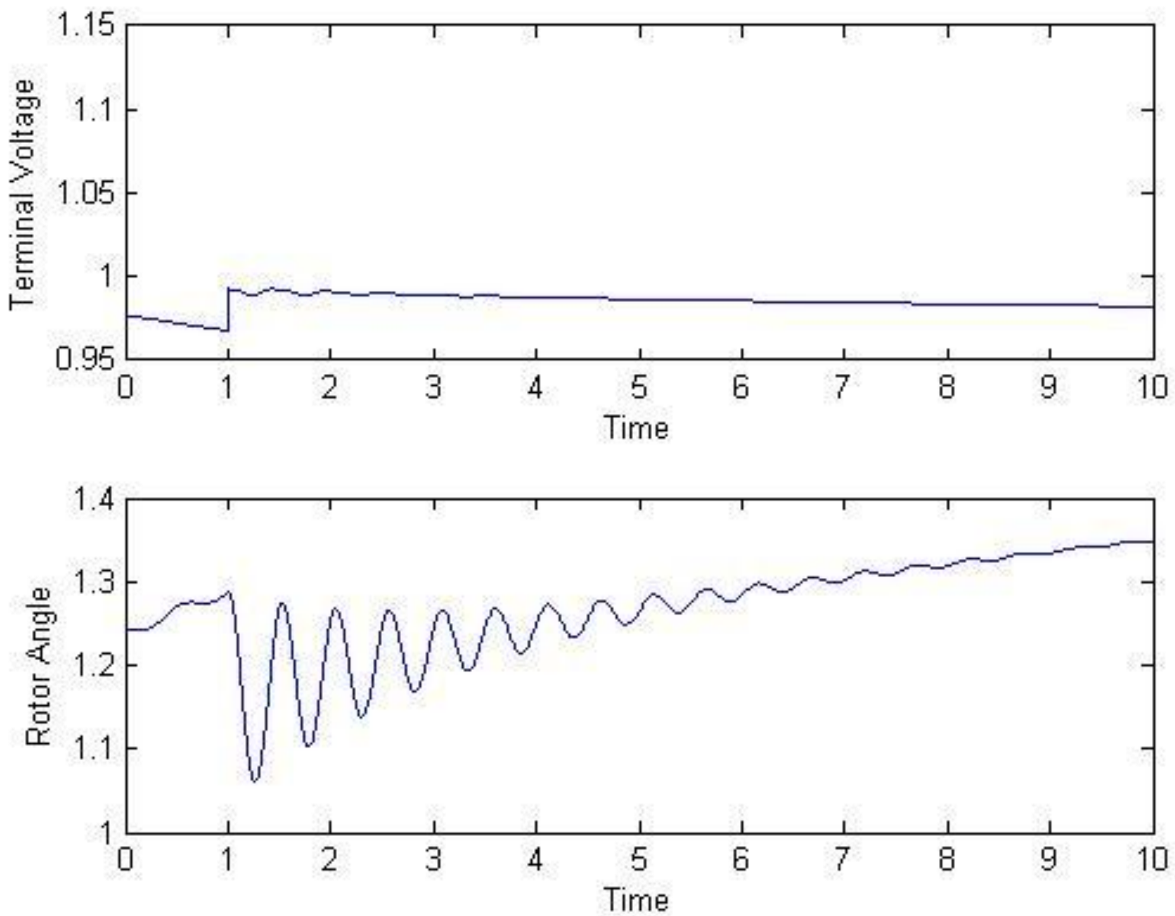


Fig 9: Variation Of Terminal Voltage & Rotor Angle with Time (with Disturbance)

Case 2:

Real Power=0.9 p.u

Reactive Power=-0.02p.u

Disturbance at T= 1seconds

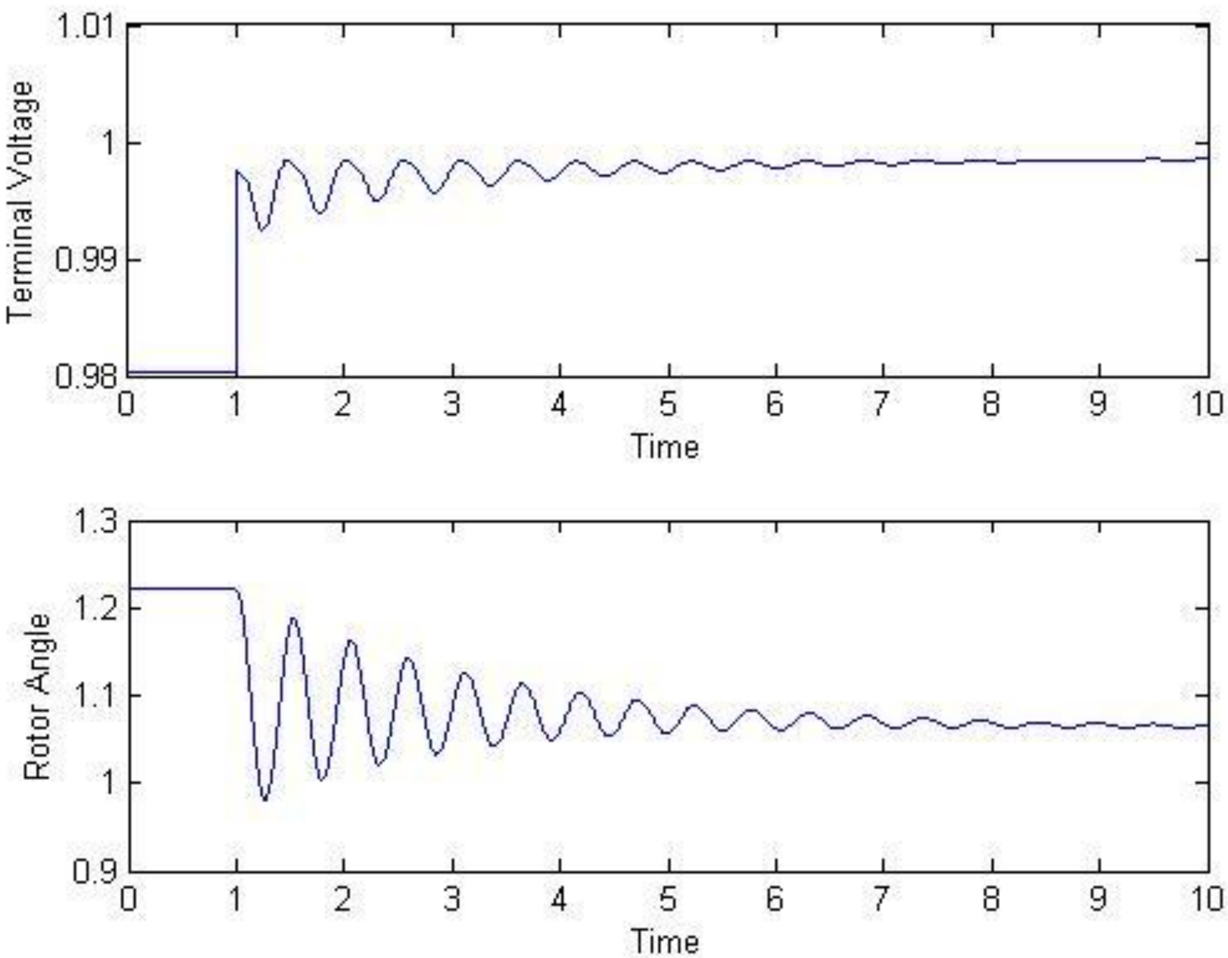


Fig 10: Variation Of Terminal Voltage & Rotor Angle with Time (with Disturbance)

Case 3:

Real Power=0.3p.u

Reactive Power=0.02 p.u

Disturbance at T= 1seconds

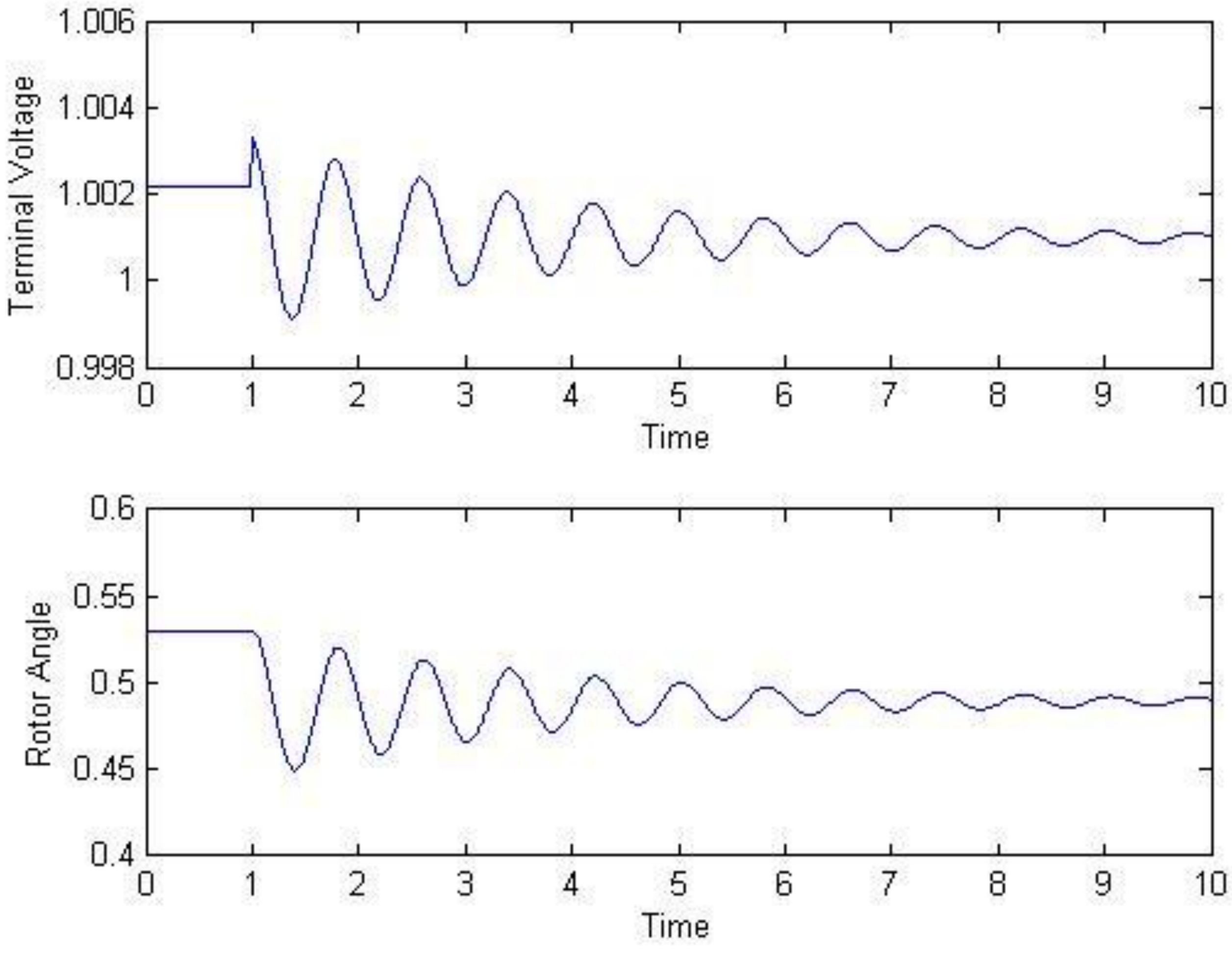


Fig 11 : Variation Of Terminal Voltage & Rotor Angle with Time (with Disturbance)

Case 4:

Real Power=0.3p.u
Reactive Power=-0.02p.u
Disturbance at T=1seconds

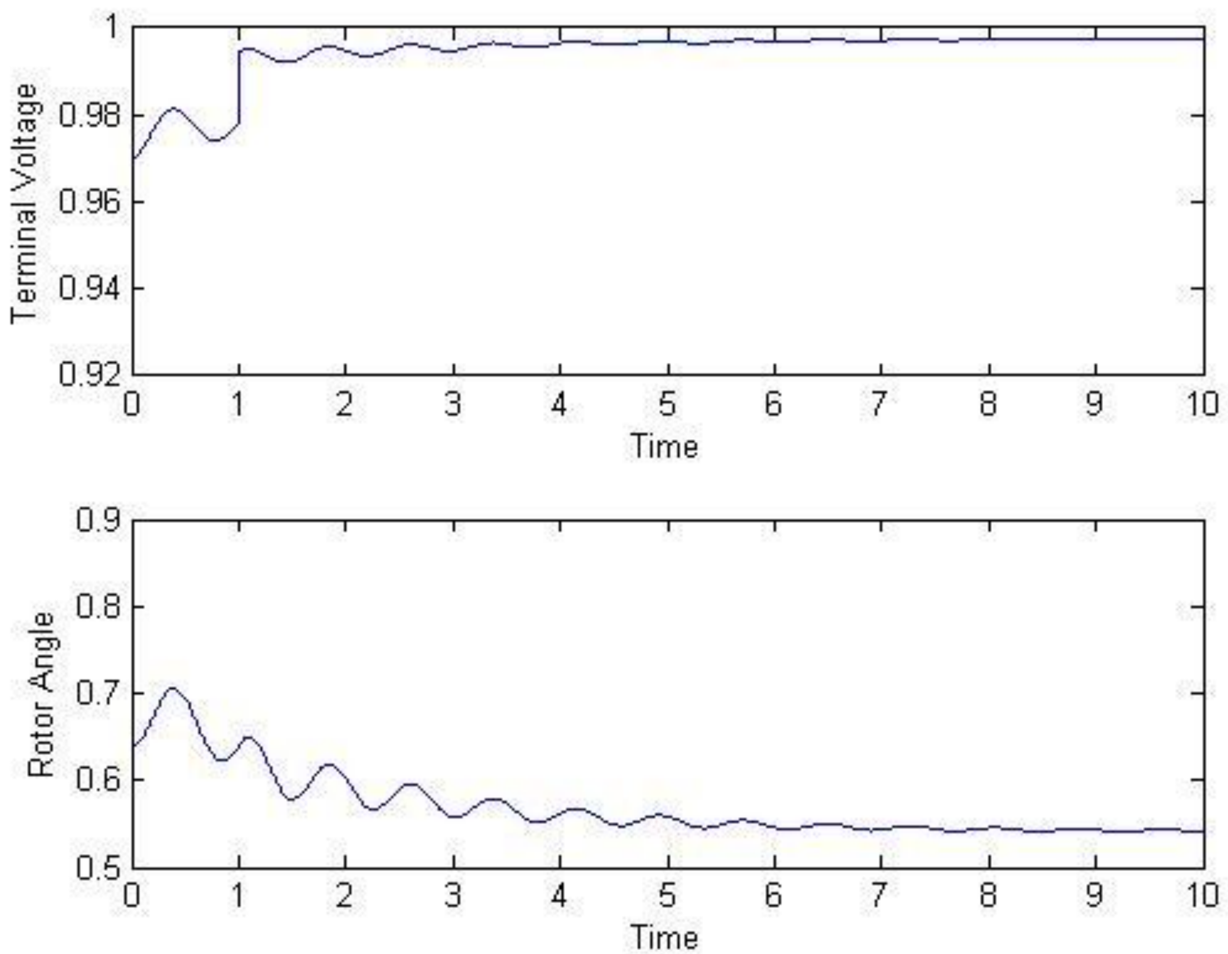


Fig 12: Variation Of Terminal Voltage & Rotor Angle with Time (with Disturbance)

Chapter 4

Integration Of The PV Generating Station

4.1 Variation of Performance Parameters

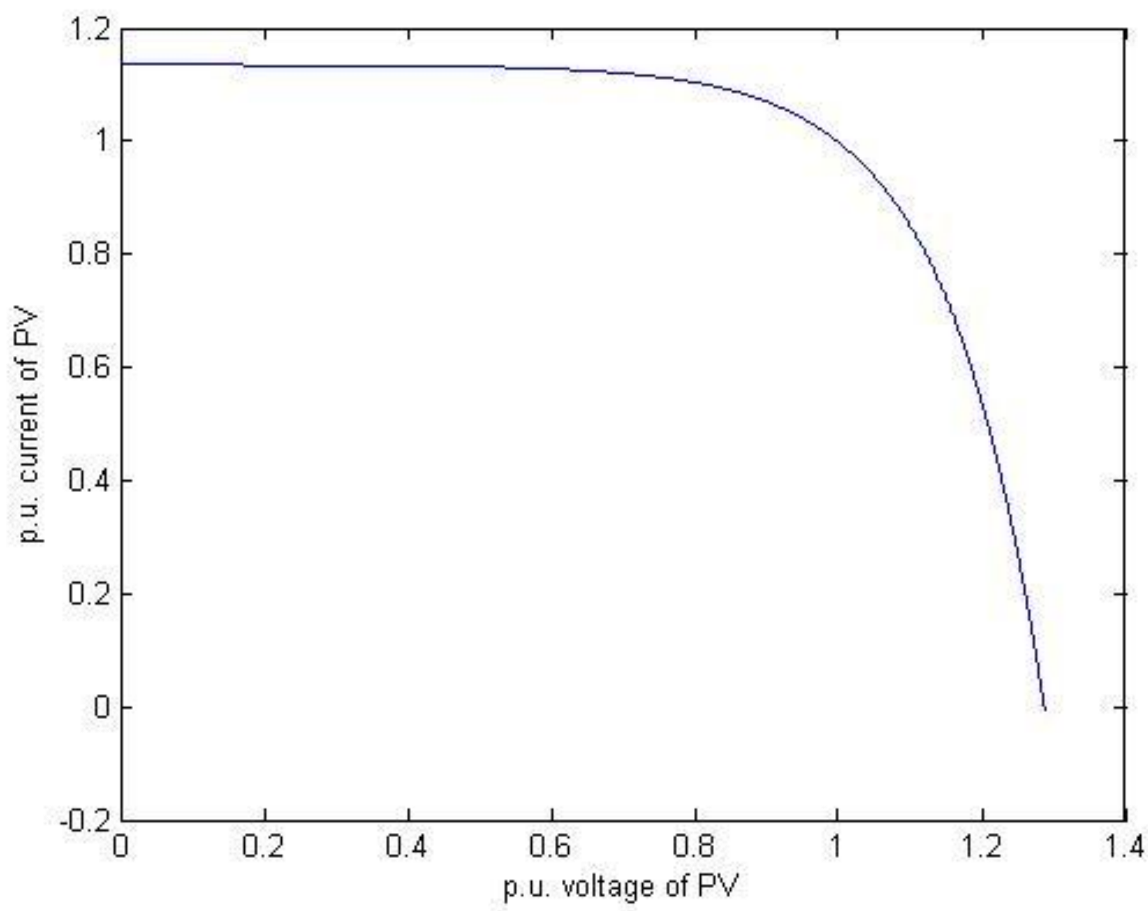


Fig 13: Variation of per unit PV current(I_{PV}) versus per unit PV voltage(V_{PV})

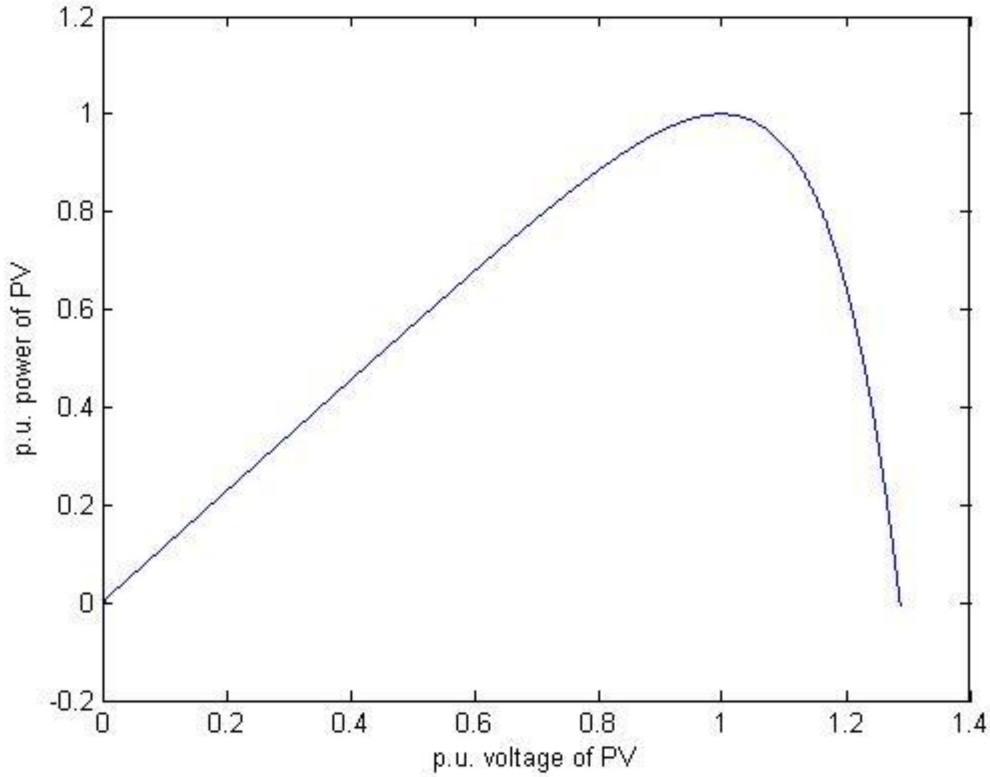


Fig 14: Variation of per unit PV power (P_{PV}) versus per unit PV voltage(V_{PV})

4.2 Critical Angle Determination

From the table below it can be seen that our computational results show that the critical operating condition occurs φ_o=65.724^o.This is so because at that particular angle the system oscillation mode goes from negative to positive, with increasing value of PV power penetration. Beyond that point the PV supplies damping torque and damages the small signal stability of the power system.

Computational results of the example power system when total active power received at the infinite busbar is fixed at 1.0 p.u. (Pt 0 + Ppv0 = 1.0 p. u.)

P_{t0}	P_{pv0}	φ_0(degree)	ΔT_{dt}	ΔT_{ddt}	ΔT_{dt-ac}	Oscillation mode
1.0	0.0	54.3	1.80	1.43	0.0006	-0.57±*j* 3.86
0.9	0.1	58.6	1.12	0.79	0.0015	-0.43±*j* 3.97
0.8	0.2	62.9	0.49	0.21	0.0021	-0.31±*j* 4.09
0.7	0.3	67.4	-0.09	-0.32	0.0023	-0.22±*j* 4.49
0.6	0.4	72.1	-0.62	-0.81	0.0021	-0.15±*j* 4.29
0.5	0.5	76.8	-1.11	-1.27	0.0017	-0.09±*j* 4.39
0.4	**0.6**	**81.5**	**-1.56**	**-1.68**	**0.0010**	**-0.04±*j* 4.47**
0.3	0.7	86.4	-1.97	-2.06	-0.0000	+0.01±*j* 4.55
0.2	0.8	91.3	-2.36	-2.42	-0.0012	+0.04±*j* 4.62
0.1	0.9	96.1	-2.72	-2.75	-0.0003	+0.07±*j*4.69

Computational results of the example power system when the PV power generation is fixed at 0.3 p.u. (Ppv0 = 0.3 p. u.)

P_{t0}	φ_0(degree)	ΔT_{dt}	ΔT_{ddt}	ΔT_{dt-ac}	Oscillation mode
0.1	89.6	-2.04	-2.07	-0.0000	-0.01±*j*8.13
0.2	85.8	-1.75	-1.81	0.0001	-0.06±*j*8.09
0.3	81.9	-1.45	-1.55	0.0003	-0.12±*j*8.05
0.4	78.2	-1.14	-1.27	0.0006	-0.17±*j*7.99
0.5	74.6	-0.81	-0.99	0.0010	-0.23±*j*7.93
0.6	70.9	-0.46	-0.67	0.0016	-0.29±*j*7.85
0.7	67.5	-0.09	-0.33	0.0023	-0.36±*j*7.76
0.8	64.1	0.33	0.05	0.0031	-0.44±*j*7.64
0.9	60.8	0.80	0.49	0.0042	-0.52±*j*7.51
1.0	57.6	1.34	0.97	0.0056	-0.61±*j*7.35

Chapter 5

Analysis of the Hybrid Generation System

5.1 Linear System Modeling (Eigen Value)

$$\begin{bmatrix} \Delta\dot{\partial} \\ \Delta\dot{\omega} \\ \Delta\dot{E}_q' \\ \Delta\dot{E}_{fd} \\ \Delta\dot{V}_{dc} \\ \Delta\dot{I}_{pv} \end{bmatrix} =$$

$$\begin{bmatrix} 0 & \omega_0 & 0 & 0 & 0 & 0 \\ \left[-\frac{1}{M}\left(\frac{K_{pm}K_{ac}B_6}{1-B_4K_{ac}}+K_1\right)\right] & -\frac{D}{M} & \left[-\frac{1}{M}\left(\frac{K_{pm}K_{ac}B_7}{1-B_4K_{ac}}+K_2\right)\right] & 0 & \left[-\frac{1}{M}\left(\frac{K_{pm}K_{ac}B_8}{1-B_4K_{ac}}+K_{pdc}+K_{p\varphi}K_{dc}\right)\right] & 0 \\ \frac{K_4}{T'_{d_0}} & 0 & \frac{K_3}{T'_{d_0}} & \frac{1}{T'_{d_0}} & \frac{K_{qdc}+K_{p\varphi}K_{dc}}{T'_{d_0}} & 0 \\ \frac{-K_A}{T_A}\left(\frac{K_{vm}K_{ac}B_6}{1-B_4K_{ac}}+K_5\right) & 0 & \frac{-K_A}{T_A}\left(\frac{K_{vm}K_{ac}B_7}{1-B_4K_{ac}}+K_6\right) & \frac{-1}{T_A} & \left[-\frac{K_A}{T_A}\left(\frac{K_{vm}K_{ac}B_8}{1-B_4K_{ac}}+K_{vdc}+K_{v\varphi}K_{dc}\right)\right] & 0 \\ \left(\frac{K_{dm}K_{ac}B_6}{1-B_4K_{ac}}+C_3\right) & 0 & \left(\frac{K_{dm}K_{ac}B_7}{1-B_4K_{ac}}+C_4\right) & 0 & \left(\frac{K_{dm}K_{ac}B_8}{1-B_4K_{ac}}+C_5\right) & C_6 \\ 0 & 0 & 0 & 0 & C_2 & C_1 \end{bmatrix} \begin{bmatrix} \Delta\partial \\ \Delta\omega \\ \Delta E_q^{'} \\ \Delta E_{fd} \\ \Delta V_{dc} \\ \Delta I_{pv} \end{bmatrix}$$

Chapter 6

Integration Of Some Proposed Controllers To The System

Using only DC controller:

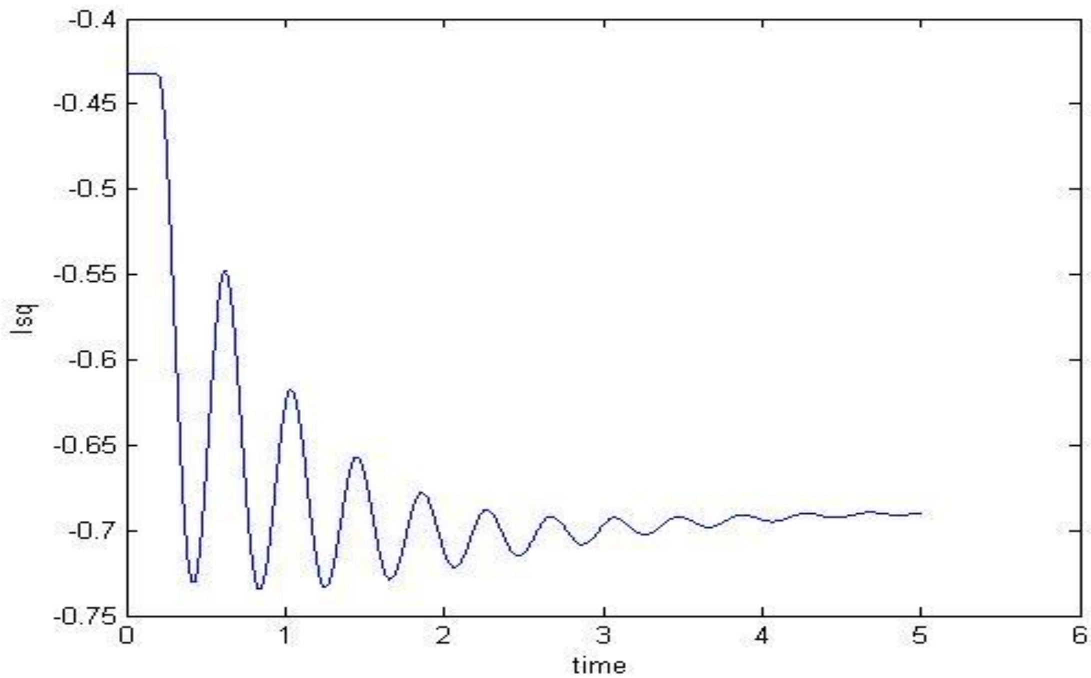


Fig 15: Variation of I_{sq} with Time

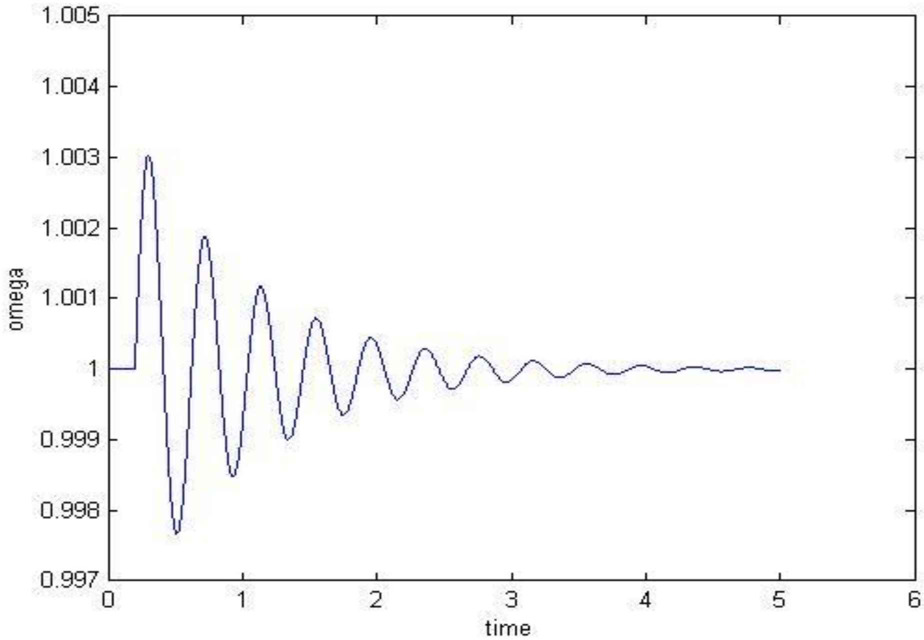


Fig 16: Variation of ω versus Time

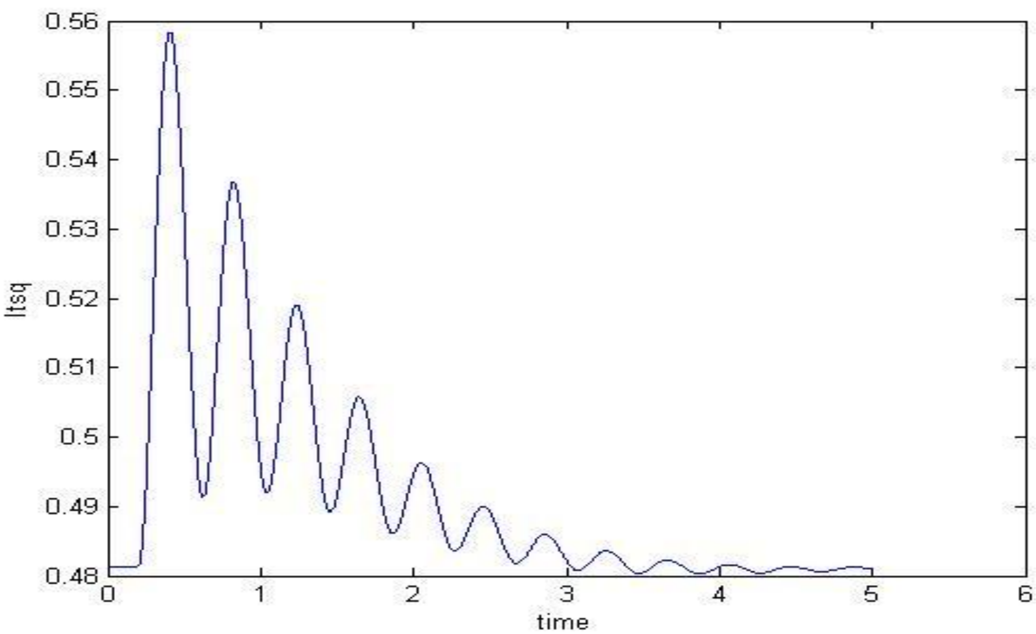


Fig 17: Variation of I_{tsq} versus Time

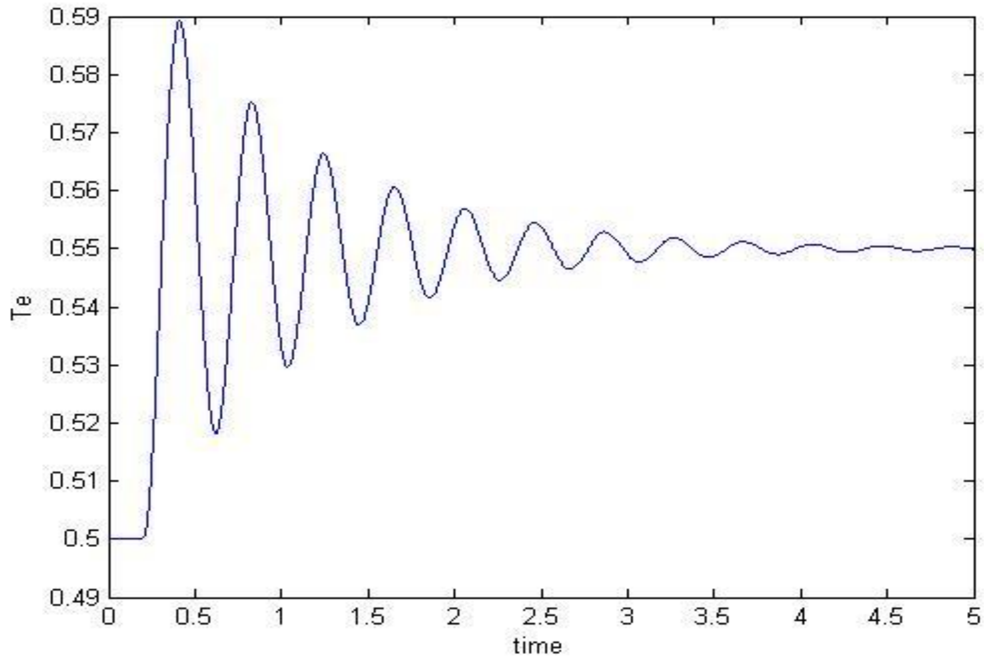


Fig 18: Variation of T_e versus Time

Using Only M controller:

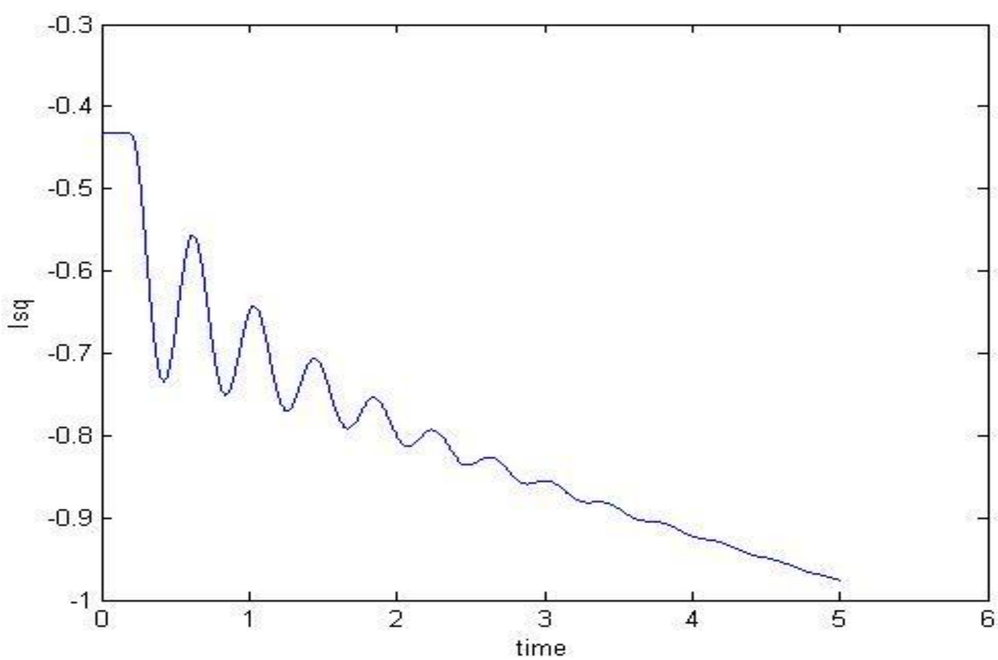


Fig 19: Variation of I_{sq} with Time

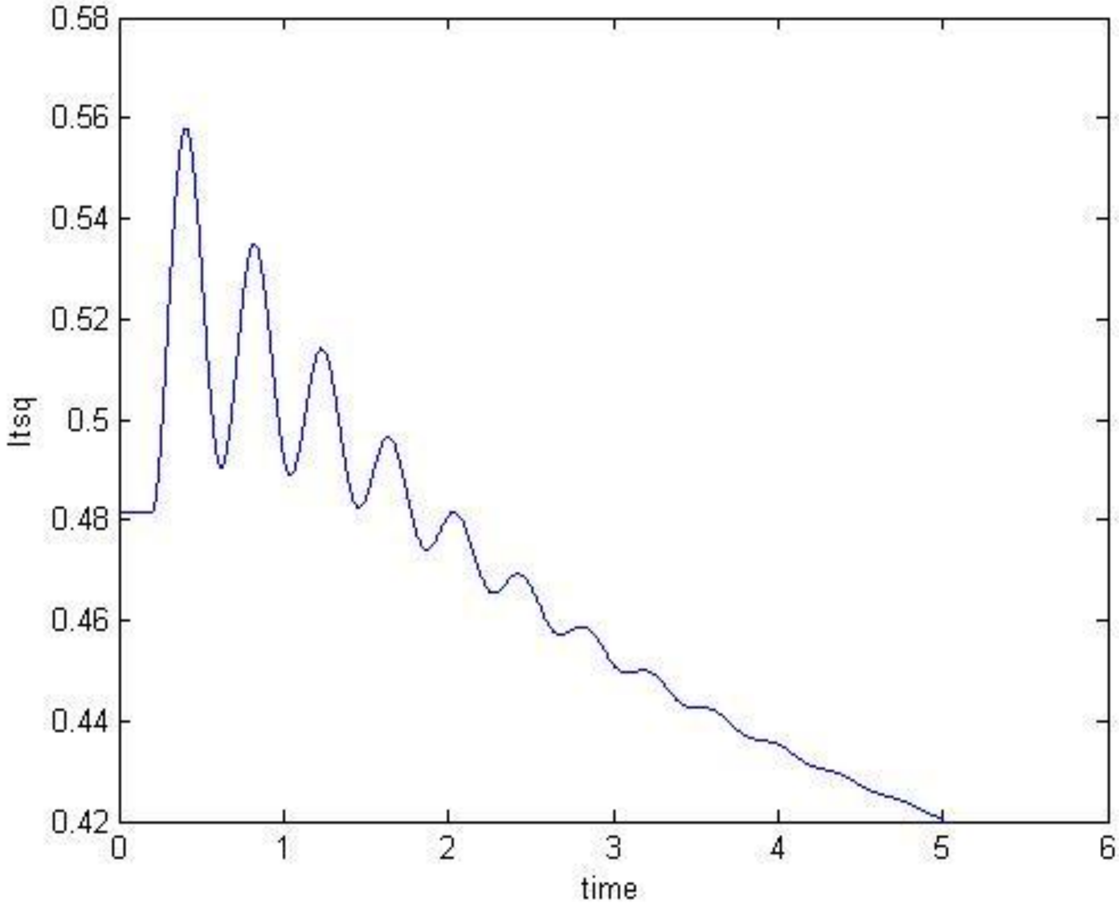


Fig 20: Variation of I_{tsq} versus Time

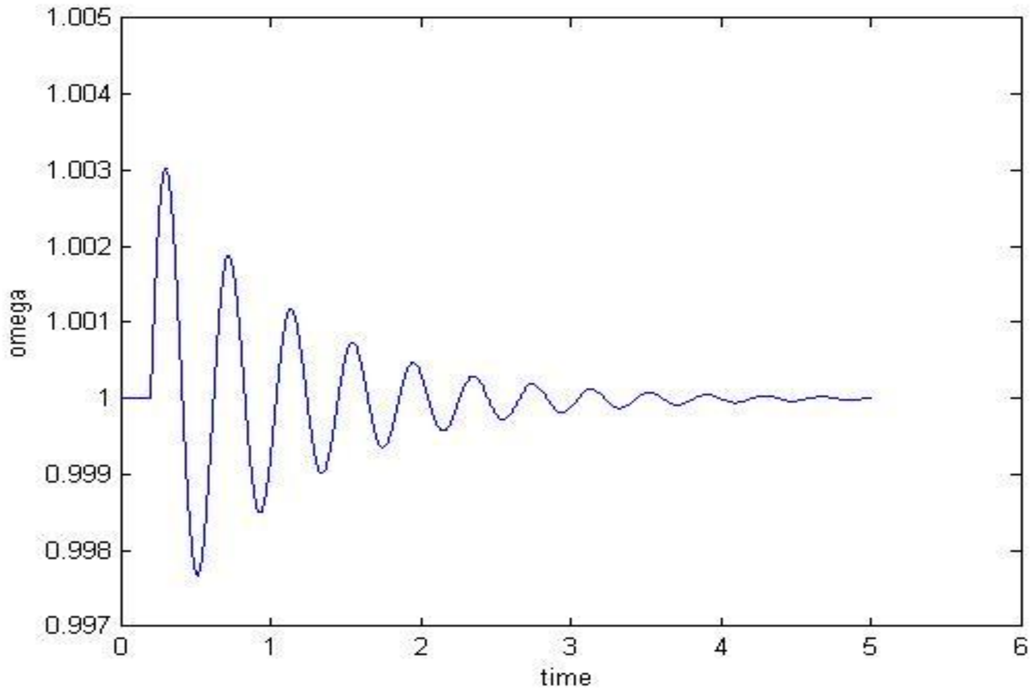


Fig 21: Variation of ω versus Time

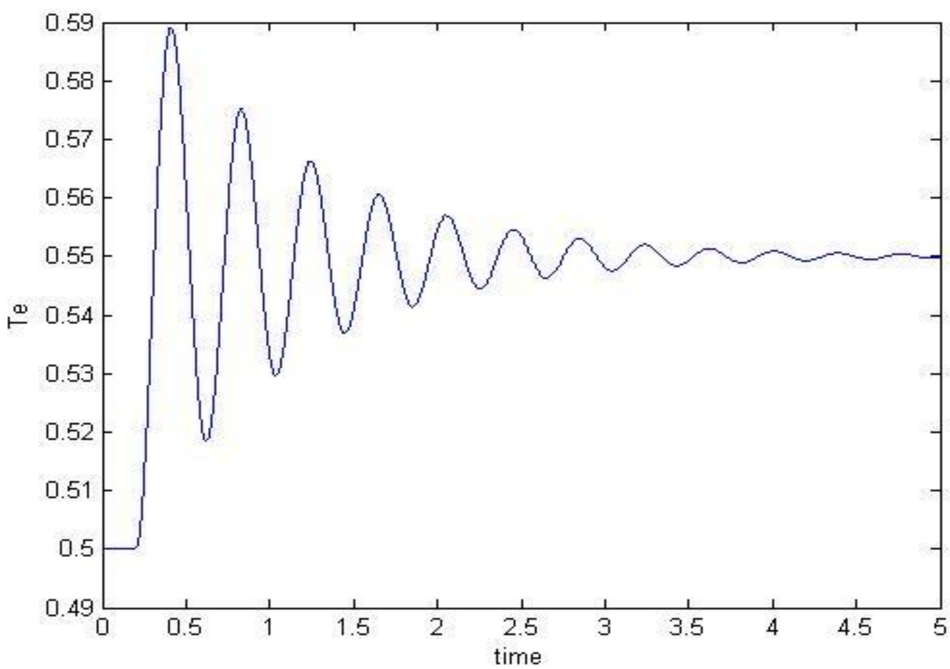


Fig 22: Variation of T_e versus Time

Using Only Shai Controller:

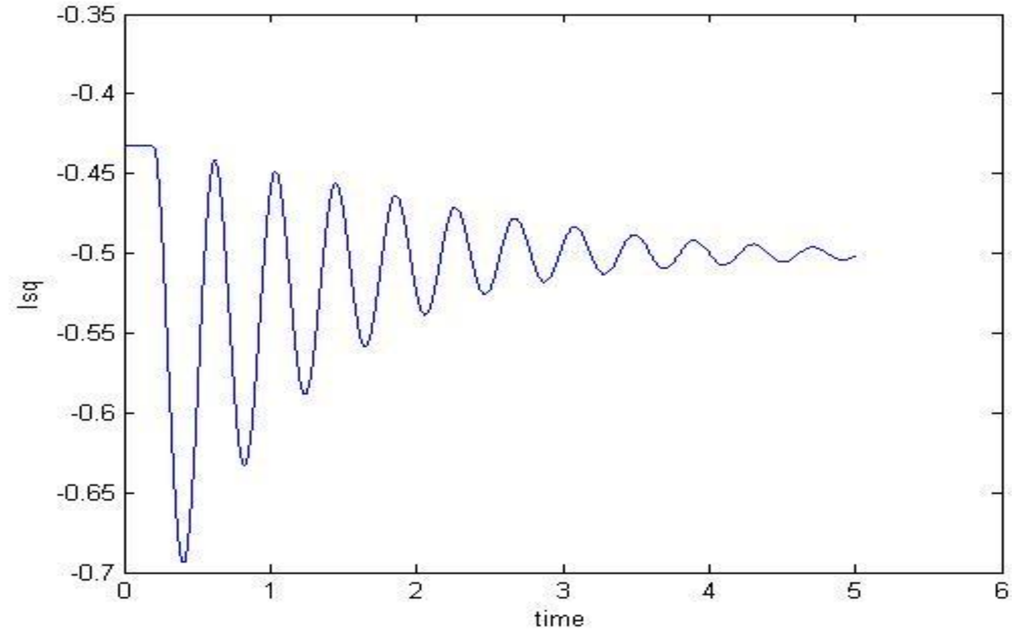


Fig 23: Variation of I_{sq} with Time

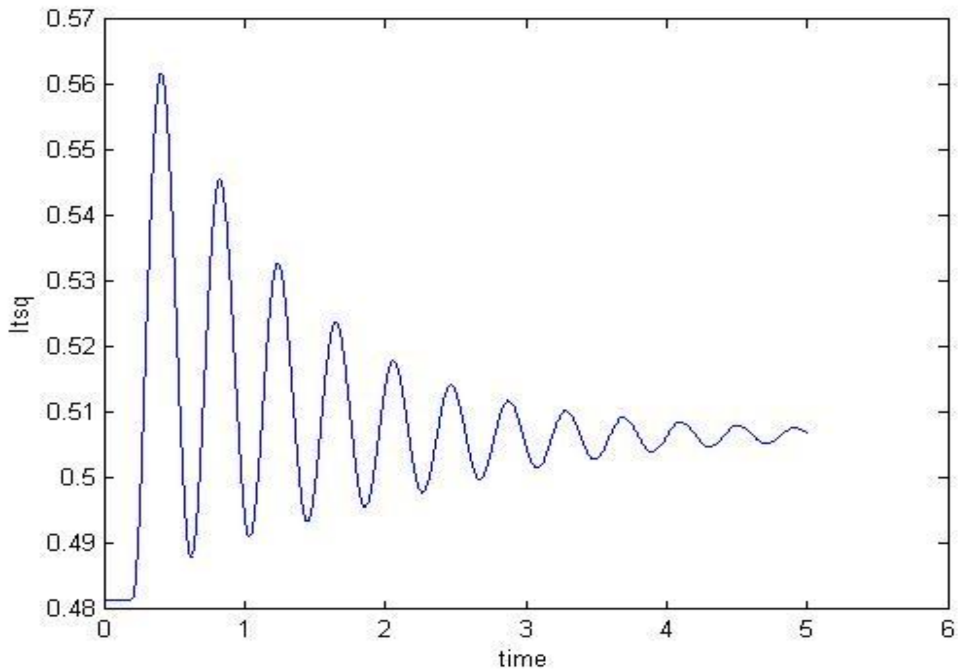


Fig 24**:** Variation of I_{tsq} versus Time

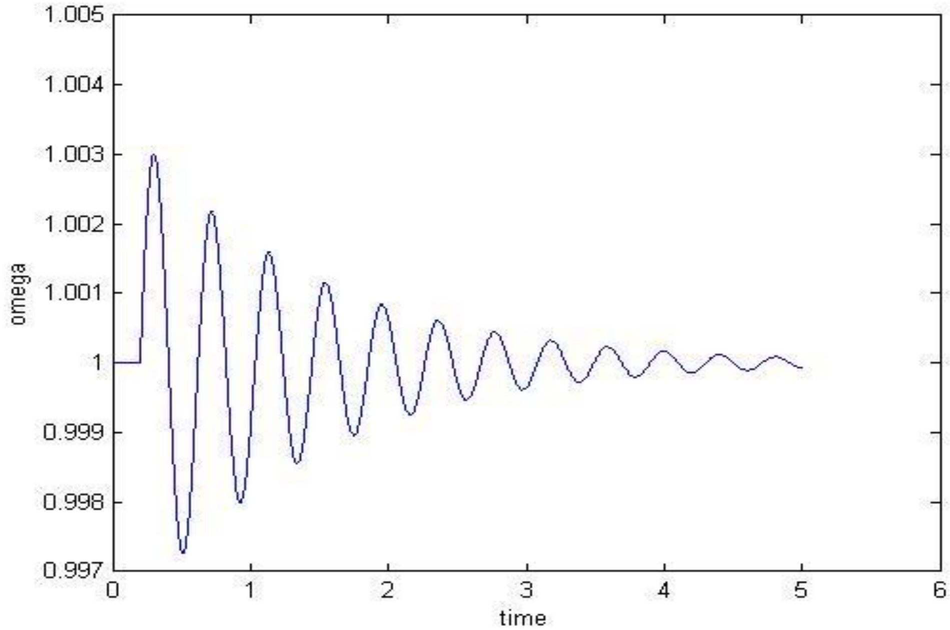


Fig 25: Variation of ω versus Time

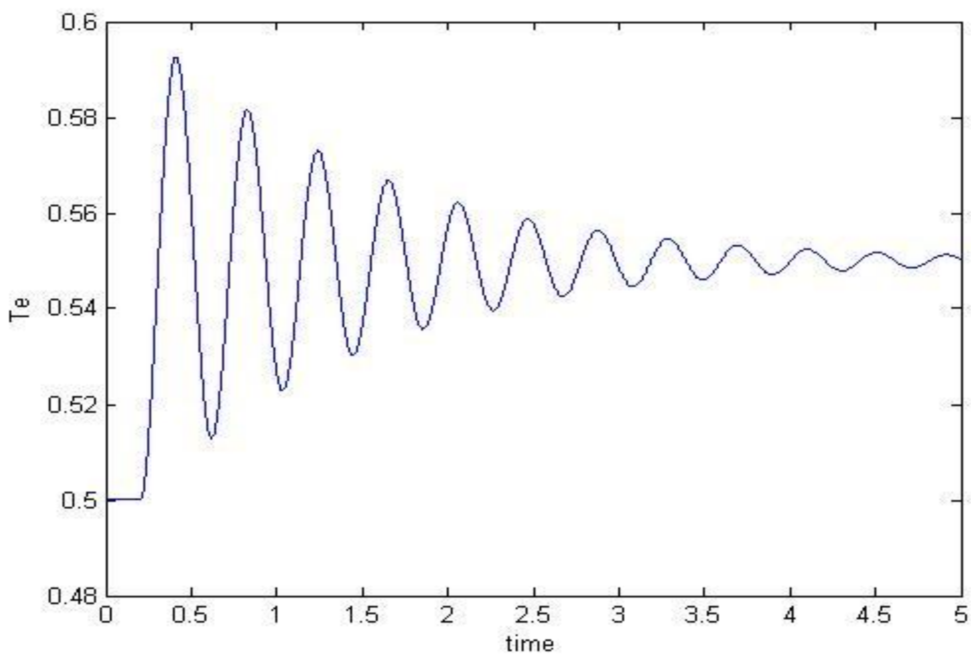


Fig 26: Variation of T_e versus Time

Using All Controller

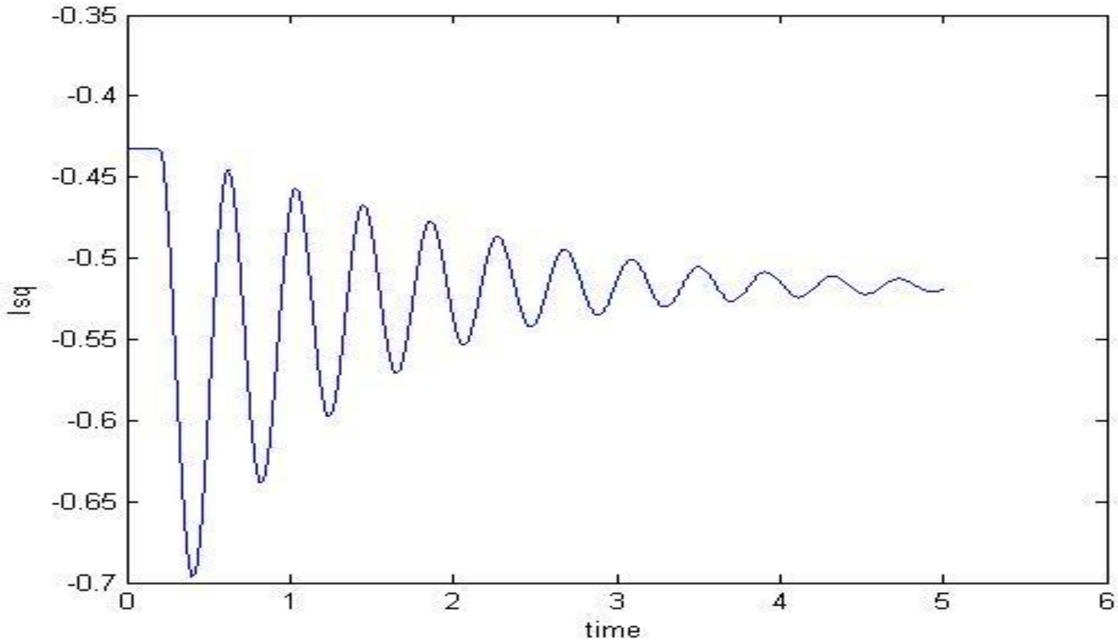


Fig 27: Variation of I_{sq} with Time

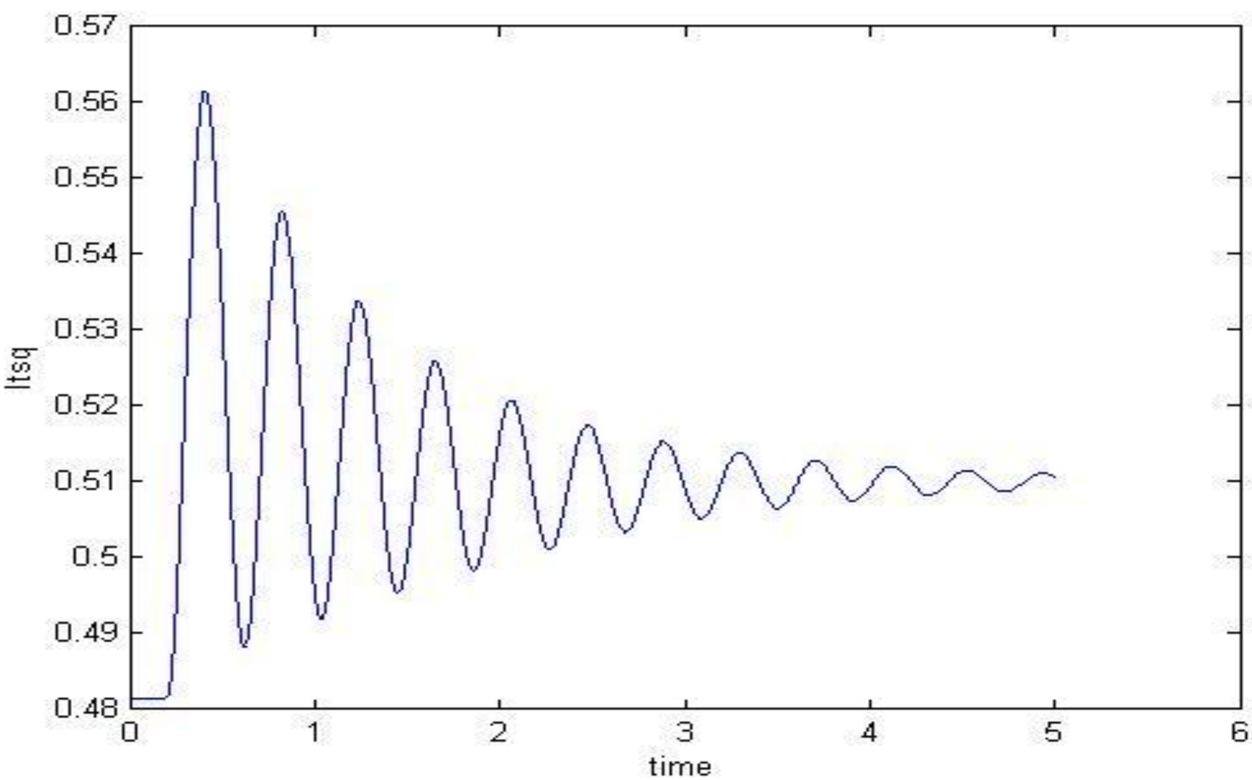


Fig 28: Variation of I_{tsq} versus Time

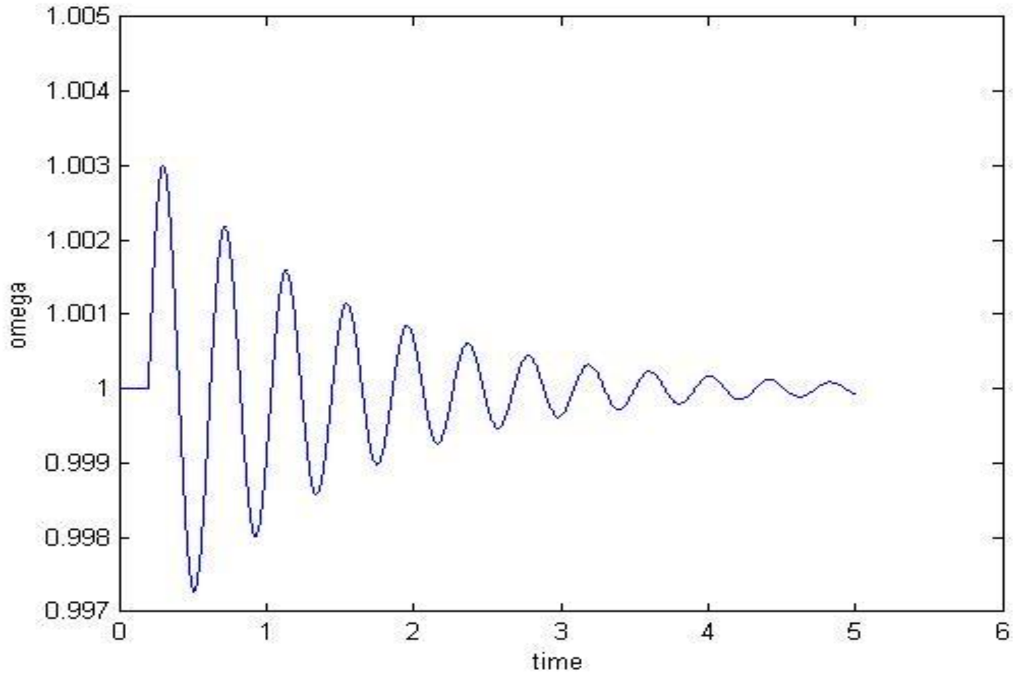


Fig 29: Variation of ω versus Time

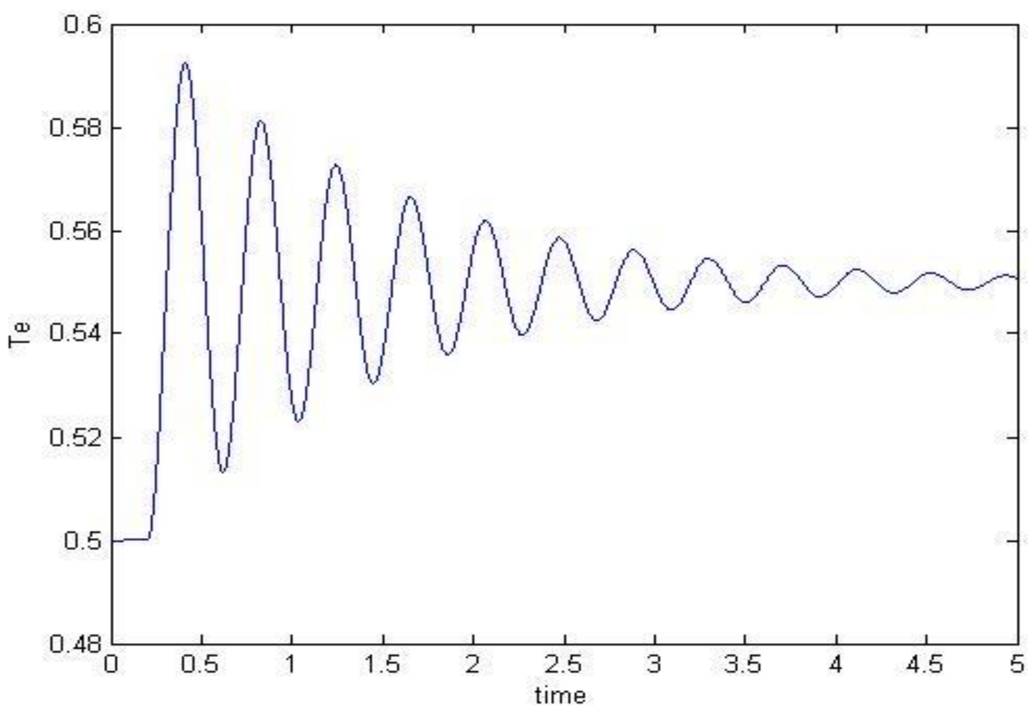


Fig 30: Variation of T_e versus Time

Chapter 7

Conclusion

The results obtained through extensive analysis and simulation (using MATLAB) that, the Photovoltaic (PV) station rather than causing extra electrochemical oscillation supplies positive or negative damping torque to the conventional power system as the operating condition vary. This is what affects the small signal stability of the hybrid generation system. Our analysis also reveals that there exists a power system critical when the damping torque contribution from the PV station changes sign, thus signifying instability in the combined system.

Our analysis also shows that the effect on the small signal stability varies with system operating conditions since damping torque contribution from the PV varies. Our analysis, linear and non-linear simulation shows that the effect of the PV on the system's small signal stability is negative beyond the critical operating condition. Although inclusion of the controllers helps in the premature attenuation of the power system oscillations, large scale PV power inclusion must be avoided.

The model used for this study was very simple and was made so purposefully for ease of analysis. Even then the model included all the necessary and basic components vital to an actual power system. Thus the study and the conclusions derived from it are valid.

LIST OF ACRONYMS AND PRINCIPAL SYMBOLS

Δ = prefix to denote the small increment of a variable

d, q =subscript to denote the d and q component of a variable

δ, ω(omega) =rotor angle and speed of the synchronous generator

E_q; E'_q= q axis voltage and transient voltage of the synchronous generator

E_{fd}, E_{fd} =excitation and output of the automatic voltage regulator

P_t,P_m =output electric from and input mechanical power to the generator

V_t,V_{tref} = terminal voltage and its reference of the generator

ω_0 = synchronous speed

M;D; T'_{d0}= inertia, natural damping coefficient, and excitation transient time constant of the synchronous generator

x_d;x_q; x'_d= d, q, and transient reactance of the synchronous generator

V_s (vs) = voltage at the bus bar where the PV power station locates

V_b = voltage at the infinite bus bar

V_c = output voltage of the DC/AC converter of the PV power station

I_{ts}(its), I_s(is), I_{sb} = line current as indicated in Figure 1

x_{ts} ,x_{sb}, = line reactance as indicated in Figure 1

V_{pv}, I_{pv} = voltage and current of the PV array

P_{pv}, P_s = output power from the PV array and the PV power station

Reference

1. Wenjuan Du, Haifeng Wang, L-Y Xiao. *European Transactions On Electrical Power(2011)*.DOI: 10.1002/etep.598.
2. K. R Padiyar. Power System Dynamics Stability and Control .177-254.
3. Sanjay Kumar Nandi, HimanshuRanjamGhosh. *Prospect Of Wind-PV-Battery Hybrid Power System As An Alternative TO Grid Extension In Bangladesh.* *www.elsevier.com/locate/energy*
4. Peter W. Sauer, M. A Pai. *Power System Dynamics And Stability*.89-120,221-277.