Dynamic Stability Study of FSIG based Hybrid Power Generation

A Thesis presented to

The Academic Faculty

By

Shafi Md. Kawsar Zaman (102422)

Muhammad Rashedul Alam Chowdhury (102428)

Md. Kamrul Hassan (102421)

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Approved by

Ashik Ahmed

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Ashik Ahmed
Project Supervisor
Dept. of Electrical & Electronic Engineering

———————————

Prof. Dr. Md. Shahid Ullah
Head of the Department
Dept. of Electrical & Electronic Engineering

———————————   ————————————

Shafi Md. Kawsar Zaman   Md. Kamrul Hassan

———————————————————

Muhammad Rashedul Alam Chowdhury

Declaration

This is to certify that the project entitled "Dynamic Stability Study of FSIG based Hybrid Power Generation" is supervised by Ashik Ahmed. This Project work has not been Submitted anywhere for a degree.

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Ashik Ahmed
 Project Supervisor
 Dept. of Electrical & Electronic Engineering

_____

Shafi Md. Kawsar Zaman
 Member

_____

Muhammad Rashedul Alam Chowdhury
 Member

_____

Md. Kamrul Hassan
 Member

Abstract

As a result of increasing environmental concern, increasing amounts of electricity are generated from renewable sources. One way of generating electricity from renewable sources is to use wind turbines. A tendency to establish more wind turbines can be observed. As a result of this, in near future wind turbines may start to influence the behavior of electrical power systems.

To investigate the impact of increasing wind turbine penetration, power system dynamics studies need to be carried out. To this end, power system dynamics simulation software is used, in which wind turbine models must be integrated to enable the investigation of increasing wind turbine penetration on power system behavior. If wind turbine models are to be integrated into power system dynamics simulation software, it must be possible to calculate the initial conditions of the dynamic model from load flow data to be able to initialize the dynamic model from load flow data to be able to initialize the dynamic simulation correctly.

Dynamic model of a synchronous generator based system and fixed speed induction generator based wind generation system, connected to grid are developed, and their steady state and dynamic performance is explored.

On establishing linearized Phillips-Heffron model, open loop Eigen values are calculated and state-space equations are used to study the stability.

Simulation results carried out by MATLAB show the potential effectiveness of enhancing dynamic stability.

Keywords: wind turbine, modelling, simulation, power system dynamics, wind profile, model initialization, initial conditions, and induction generator.

Acknowledgements

Contents

Chapter 1
Power system and Stability

1.1 Introduction:

At present the demand for electricity is rising phenomenally especially in developing country like Bangladesh. This persistent demand is leading to operation of the power system at its limit. On top of this the need for reliable, stable and quality power is also on the rise due to electric power sensitive industries like information technology, communication, electronics etc. In this scenario, meeting the electric power demand is not the only criteria but also it is the responsibility of the power system engineers to provide a stable and quality power to the consumers. These issues highlight the necessity of understanding the power system stability. In this course we will try to understand how to assess the stability of a power system, how to improve the stability and finally how to prevent system becoming unstable.

1.2 Power System:

An **electric power system** is a network of electrical components used to supply, transmit and use electric power. An example of an electric power system is the network that supplies a region's homes and industry with power - for sizable regions, this power system is known as *the grid* and can be broadly divided into the generators that supply the power, the transmission system that carries the power from the generating centers to the load centers and the distribution system that feeds the power to nearby homes and industries. Smaller power systems are also found in industry, hospitals, commercial buildings and homes. The majority of these systems rely upon three-phase AC power - the standard for large-scale power transmission and distribution across the modern world. Specialized power systems that do not always rely upon three-phase AC power are found in aircraft, electric rail systems, ocean liners and automobiles.
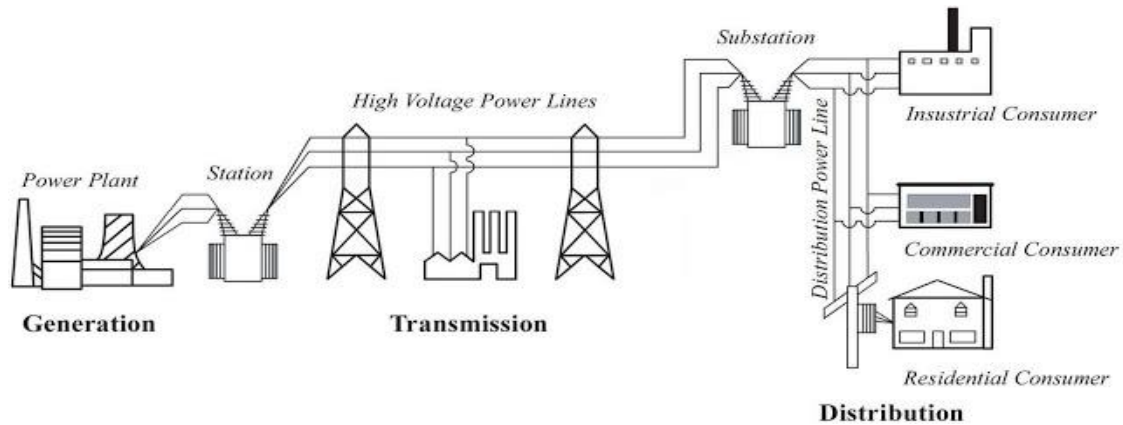
1.3 Stability:

Power system engineering forms a vast and major portion of electrical engineering studies. It is mainly concerned with the production of electrical power and its transmission from the sending end to the receiving end as per consumer requirements, incurring minimum amount of losses. The power at the consumer end is often subjected to changes due to the variation of load or due to disturbances induced within the length of transmission line. For this reason the term **power** system stability is of utmost importance in this field, and is used to define the ability of the of the system to bring back its operation to steady state condition within minimum possible time after having undergone some sort of transience or disturbance in the line.

1.4 Types of Stability:
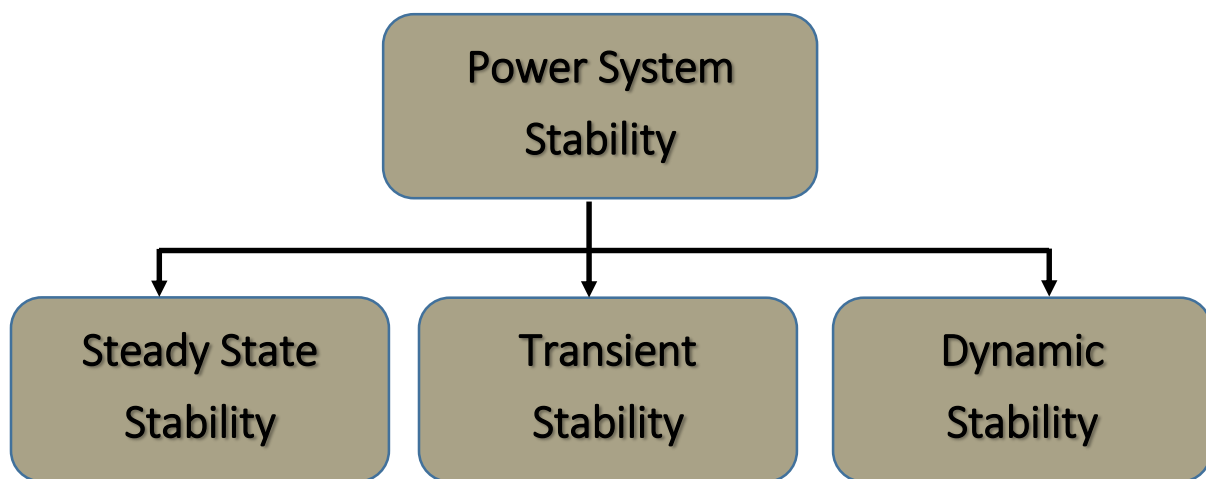
Figure 1 : The classification of stability

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1.4.1 Steady State Stability:

The steady state stability of a power system is defined as the ability of the system to bring itself back to its stable configuration following a small disturbance in the network (like normal load fluctuation or action of automatic voltage regulator). It can only be considered only during a very gradual and infinitesimally small power change. In case the power flow through the circuit exceeds the maximum power permissible, then there are chances that a particular machine or a group of machines will cease to operate in synchronism, and result in yet more disturbances. In such a situation, the steady state limit of the system is said to have reached. Or in other words the steady state stability limit of a system refers to the maximum amount of power that is permissible through the system without loss of its steady state stability.

1.4.2 Transient Stability:

Transient stability of a power system refers to the ability of the system to reach a stable condition following a large disturbance in the network condition. In all cases related to large changes in the system like sudden application or removal of load, switching operations, line faults or loss due to excitation the transient stability of the system comes into play. It in fact deals in the ability of the system to retain synchronism following a disturbance sustaining for a reasonably long period of time. And the maximum power that is permissible to flow through the network without loss of stability following a sustained period of disturbance is referred to as the transient stability of the system. Going beyond that maximum permissible value for power flow, the system would temporarily be rendered as unstable.

3LG-O (3 line to ground fault and Open)

Fault occurred   Cleared (typical 4-5 cycles)

Transient area
(approx. 0-
1sec)

Dynamic area
(approx. 1-10sec)
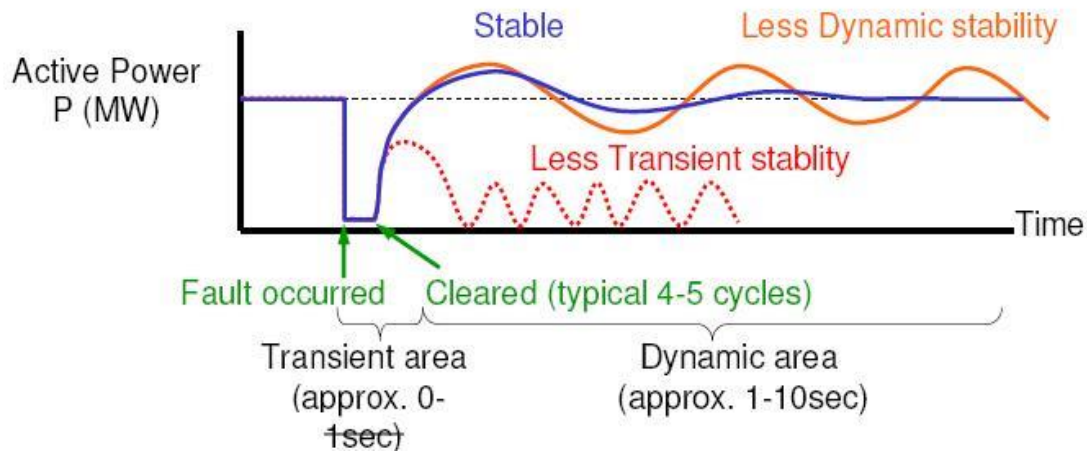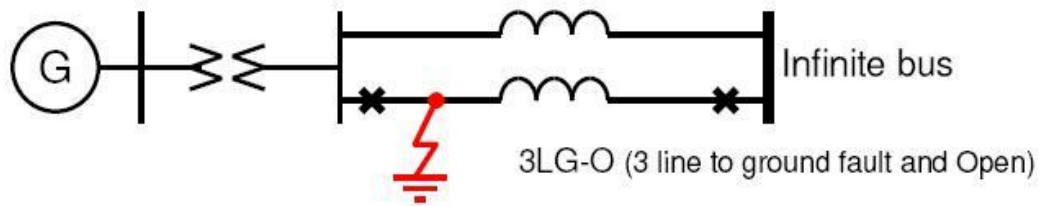
1.4.3 Dynamic Stability:

Dynamic stability of a system denotes the artificial stability given to an inherently unstable system by automatic controlled means. It is generally concerned to small disturbances lasting for about 10 to 30 seconds.
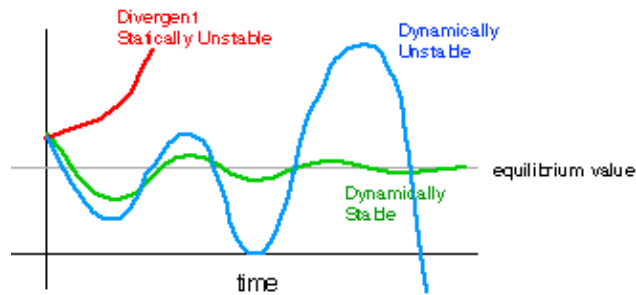
1.5 Renewable Energy Integration and Stability:

In our thesis we have focused on wind turbine based power generation which is a form of renewable energy. So we must know the stability of the renewable energy based power system. The key stability issues of renewable energy system are:

1.5.1 Frequency Stability:

- ✓ Renewable energy sources are often connected via a converter interface and have no inertia.
- ✓ Replacing synchronous generators with sources using a converter interface therefore reduces total system inertia and is more sensitive to frequency deviations.
- ✓ Thermal generators may run under minimum load if displaced by renewable energy sources.

1.5.2 Potential mitigation measures:

- ✓ Minimum system inertia i.e. minimum numbers of synchronous generators are online.
- ✓ Under frequency Load shedding.
- ✓ Energy storage with fast response.
- ✓ Demand Side management i.e. smart grid technologies.
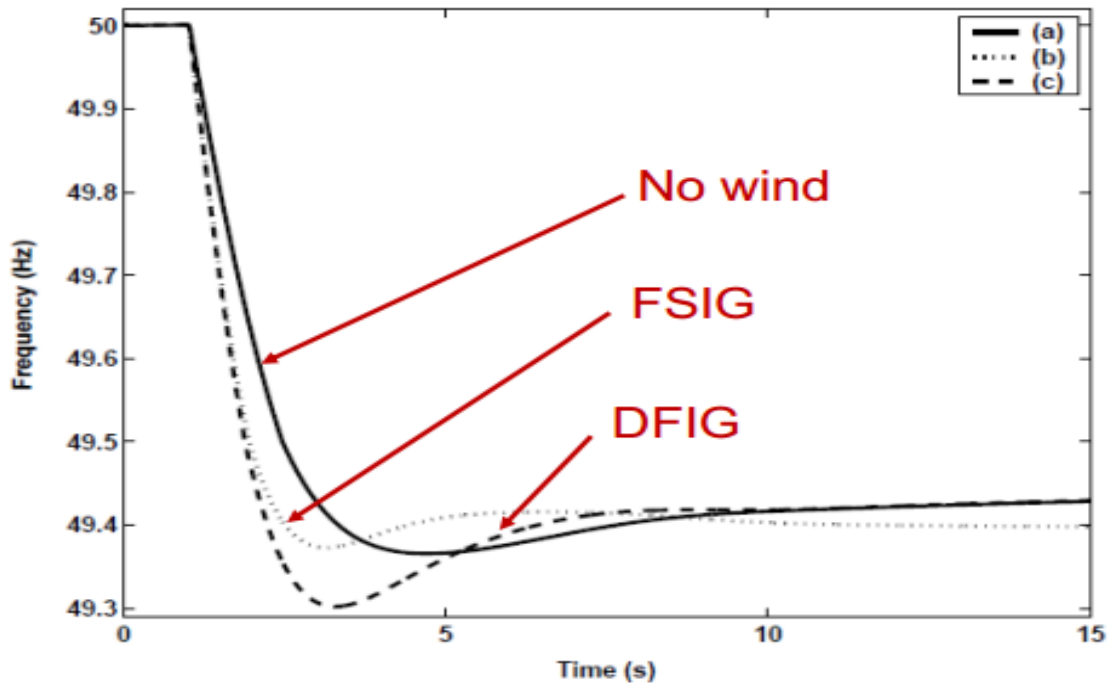
1.5.3 Transient stability:

✓ Effects of renewable energy integration on transient stability must be assessed on a case-by-case basis and depends more on distribution of synchronous generator and controller types.
✓ Some past studies indicate that for moderate penetrations e.g. 30-40% renewable energy sources do not significantly affect transient stability.

1.5.4 Potential mitigation measures:

Depending on grid characteristics, it may be necessary to limit penetrations of renewable energy sources.

1.5.5 Voltage Stability:

✓ Renewable energy sources with limited or no reactive power control will decrease voltage stability.
✓ Integrated renewable energy sources into weak parts of the grid can actually improve voltage stability.

1.5.6 Potential mitigation measures:

✓ Use renewable energy sources that are capable of reactive power control.
✓ Connect renewable energy sources at weak part of the grid.

Chapter 2
Overview of FSIG based Wind Power Generation

2.1. Introduction

An induction generator or *asynchronous generator* is a type of alternating current (AC) electrical generator that uses the principles of induction motors to produce power. Induction generators operate by mechanically turning their rotors faster than the synchronous speed corresponding to the electric grid they are connected with. A regular AC asynchronous motor usually can be used as a generator, without any internal modifications. Induction generators are useful in applications such as mini hydro power plants, wind turbines, and in reducing high-pressure gas streams to lower pressure, because they can recover energy with relatively simple controls.

An induction generator must be excited with a leading voltage. This is usually done by connection to an electrical grid; sometimes, however, they are self-excited by using phase-correcting capacitors. Because of this, induction generators cannot usually "black start" a de-energized distribution system.

For an FSIG (Fixed Speed Induction Generator):-

✓ Only fix speed operation possible (stall control required)
✓ Reactive power compensation required
✓ No reactive power control capability. Additional devices required
✓ TSCs (Thyristor switched capacitors)
✓ STATCOMs
✓ Risk of dynamic voltage collapse

Typically, wind generators based on induction generators are asked to disconnect in case of voltage dips.

Wind power industry is developing rapidly, more and more wind farms are being connected into power systems. In the next years, there will be more significant growth in wind energy. Although the great development in the technology of electrical generation from wind energy, there is only one way of generating electricity from wind energy is to use wind turbines that convert the energy contained in flowing air into electricity. Fixed speed wind turbines utilize squirrel cage induction generator directly connected to the grid to produce the electricity. Wind energy is not a constant source of energy. It varies continuously and gives energy in sudden bursts. About 50% of the entire energy is given out in just 15% of the operating time. Wind strengths vary and thus cannot guarantee continuous power.

2.2. Environmental Aspects of Wind Power

Harnessing power from the wind is one of the cleanest and most sustainable ways to generate electricity as it produces no toxic pollution or global warming emissions. Wind is also abundant, inexhaustible, and affordable, which makes it a viable and large-scale alternative to fossil fuels.

Atmospheric emissions

No direct atmospheric emissions are caused by the operation of wind turbines. The indirect emission from the energy used to produce, transport and decommission a wind turbine depends on the type of primary energy used.

Liabilities after decommissioning

Electricity from wind turbines has no liabilities related to decommissioning of obsolete plants. Today, most metal parts of wind turbines can be re-cycled. In a very near future other parts, such as electronics and blades, will be recycled almost 100p.c.

Energy balance

The direct environmental effects related with manufacturing of wind turbines is similar to those of other equipment production processes, and the indirect environmental effects of the energy used to produce a wind turbine depend on the type of primary energy used. Several early investigations have shown, that the energy invested in production, installation, operation & maintenance and decommissioning of a typical wind turbine has a "pay-back" time of less than a year of operation.

Land use

Wind energy is diffuse and collecting energy from the wind requires turbines to be spread over a wide area. Onshore wind farms have the advantage of dual land use. 99% of the area occupied by a wind farm can be used for agriculture or remain as natural habitat. Furthermore, part of the installations can be made offshore. Consequently, limited area of land is not a physical constrain for wind power utilization, as it could be for large scale utilization of biomass in energy production.

2.3 Technical Merits of Wind Power:

Fossil fuels make the world's economy vulnerable to supply shocks and the price of fossil fuel especially crude oil, can single-handedly threaten world economic growth. About 40% of the world's energy comes from oil, much of which is imported by the industrialized nations therefore, any significant restrictions to their sources of oil, will result to considerable damage of their economies. Wind power can be the best solution for this.

In terms of solar energy,

1. One wind turbine generated the same amount of electricity per kWh as about 48704 solar panels. To manufacture and maintain 48704 solar panels, 28,126,560 kWh must be consumed. It took 23,822,339 kWh more to produce 48704 solar panels than it takes to produce one wind turbine.

2. When comparing the amount of CO_2 released per kWh during a wind turbine and solar panel's life cycle, the wind turbine produced 4.64 grams of CO_2/1kWh while the solar panel produced 70 grams of CO_2/1kWh. This means the wind turbine released less CO_2 than the solar panel to the atmosphere.

3. Energy balance is the amount of time needed to pay back the energy consumed. The lower the payback time, the sooner the machine starts producing energy that is renewable. The wind turbine took only 6.6 months to repay its energy balance while the solar panel took 3.2 years. Because the turbine took less time to repay its energy balance, the turbine can then profit from the energy generated after its payment.

4. Energy Return on Investment (EROI) is used to compare the quantity of energy supplied to the quantity of energy used in supply process. The higher the ratio, the less energy is consumed in producing the energy. The wind turbine's EROI is approximately 36.5:1 while solar energy has an EROI of 5:1. We can deduce that that the wind turbines return more energy for a certain amount of energy invested.

Wind power is one of the cheapest sources of electricity and nuclear power as one of the more expensive.

Biomass energy is expensive, insufficient, and harmful to environment, consume more fuel and require more land than wind power generation.

2.4. Economical Merits of Wind Power:

Wind energy benefits the economy in three ways:

- ✓ Wind parks bring economic development to the rural communities that host them.
- ✓ Developing our nation's wind energy resources creates demands for turbines and turbine components, which stimulates the manufacturing sector.

✓ Wind energy helps to stabilize wholesale electricity costs, which is good for both consumers and for businesses.

It makes sense that clean, renewable wind energy is good for the environment. For this reason the wind energy consumption is increasing day by day with respect to other renewable energies also there is a total installed capacity in different countries in 2013 which are shown below:
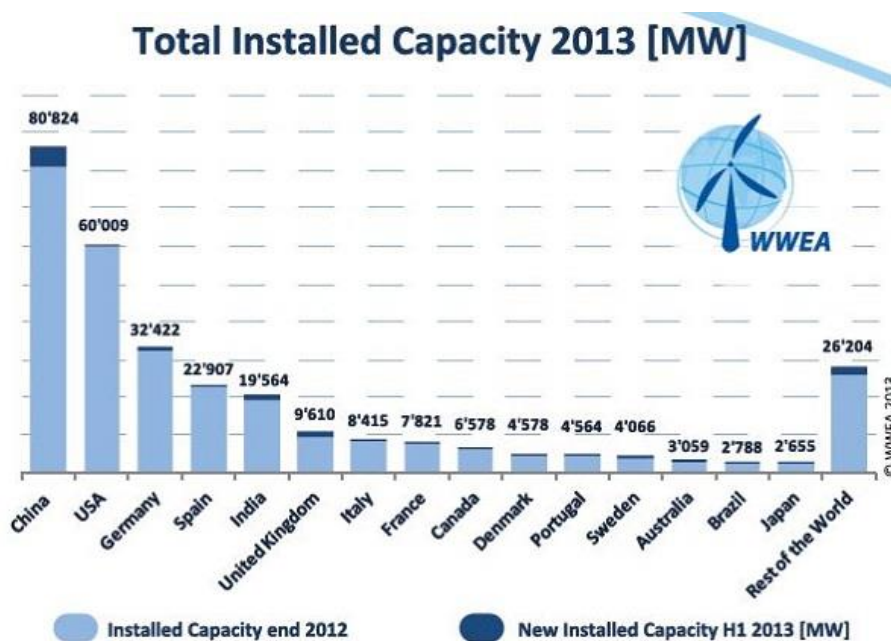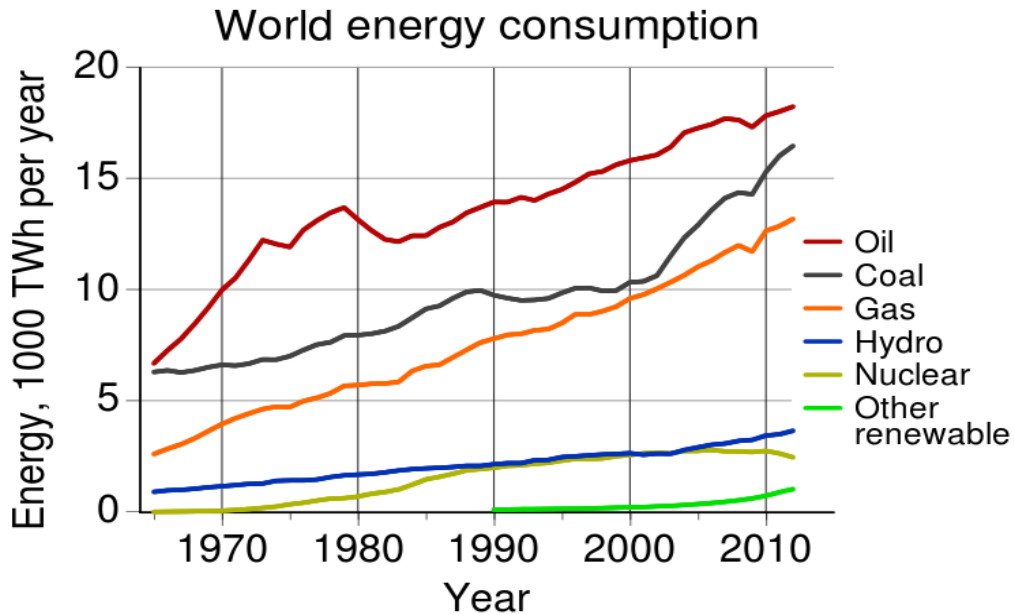
2.5. Wind Power Application:

As the business world embraces a new era that demands, profitability and environmental accountability, wind power provides economically viable solutions.

The cost of electricity is increasing year by year with no relief in sight. Excess CO2 emitted into the environment is contributing to our legacy of global warming. Harnessing the power of the wind to produce electricity is a clean and renewable way to make a difference.

From irrigation pivots and processing equipment to simple heating and lighting applications, rural farms can consume large amounts of electricity from wind power.

Therefore it is used in-

➢ Generating Power at Remote Sites:
➢ Hybrids
➢ Low-Power Applications
➢ Village Electrification
➢ Interconnecting with the Utility
➢ Farming the Wind
➢ Heating
➢ Pumping Water

2.6. Why use Induction Generator?

✓ As Wind speed doesn't remain constant, that's why generator used is induction type.
✓ Most Distributive Generation systems in the developed countries (especially Europe and America) incorporate power generating units by induction generator. For its simplicity robustness, and small size per generated Kw, the induction generator is favored for small hydro and wind power plants.
✓ Power electronics and microcontroller technologies have given a decisive boost to induction generators for small scale generation because they enable very advanced and inexpensive types of control, new techniques of reactive power supplements, and asynchronous injection of power into the grid.

2.7. Operating Principles of Induction Generator:

▪ Uses the principle of electromagnetic induction.
▪ Electric power is produced when the rotor is turned faster than the synchronous speed.
▪ A prime mover (wind turbine) drives rotor above synchronous speed.
▪ Opposing rotor flux cuts the stator coils, an active current flows in stator coils, and the motor now operates as generator.

Chapter 3
Synchronous Machine Modelling

3.1 Introduction:

In this chapter we will discuss the modeling and stability analysis of a HVAC link. The most important component of the system is the synchronous generator with its associated controls–excitation and prime mover. The dynamics of a synchronous generator is illustrated by taking up the example of a single machine connected to an infinite bus (SMIB). Although a power station is consists of more than one generator they all can be represented by one single machine. The accuracy of this kind analysis depends on the system data, type of study considered etc. Analysis of the dynamic behavior of a synchronous machine needs the simplification of the SMIB system.

3.2 Modeling of a SMIB System

3.2.1 System Model

We considered a single machine infinite bus model to serve our purpose. One port of the system is connected to the generator terminals while the other port is connected to an infinite bus. To neglect the transients in the external network the analysis involves low frequency behavior of the system which is an important assumption for the analysis.The system considered is shown in figure 3.1:
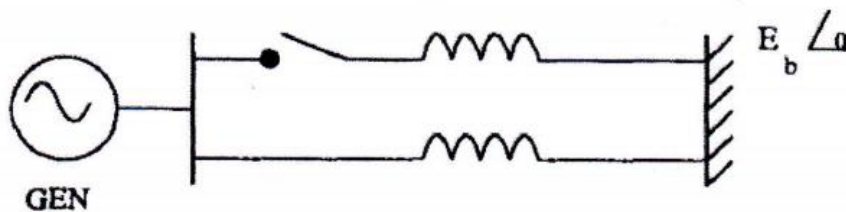
Fig 3.1: Single Machine Infinite Bus System

The synchronous machine considered is shown in Fig. 3.2. This shows a three phase armature windings (a, b and c) on the stator and four windings on the rotor including the field winding 'f'. The damper circuits in the salient pole machine or the eddy-current effects in the rotor 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 are shown in Fig. 3.2. The number of damper coils represented can vary from zero (in the simplest model) to five or more using Jackson-Winchester model. However the most detailed model used extensively in power system dynamic studies is limited to 3 damper coils. (It is also easier to obtain the parameters of this and simpler models). The following assumptions are used in the derivation of the basic equations of the machine.

1. The mmf in the air gap is distributed in sinusoidal form and the harmonics are neglected.

2. Saliency is restricted to the rotor. The effect of slots in the stator is neglected.

3. Magnetic saturation and hysteresis are ignored.
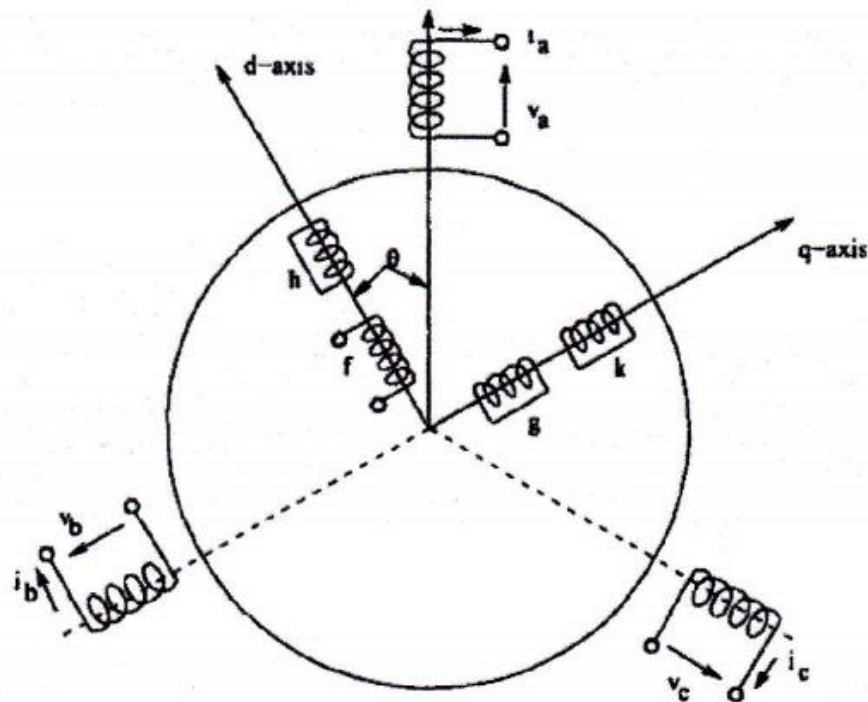
Fig 3.2: Synchronous machine

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The analytical solutions of the equations that we get from the above figure are almost impossible because of the time variant inductance matrix. So it would be advantageous if the time-varying machine equation can be transformed to a time invariant set. This would result in the simplification of the calculations both for steady state and transient conditions.

Parks Transformation transforms time variant AC quantities to time invariant DC quantities. The stator coils 'a', 'b' and 'c' from figure 3.2 are replaced by fictitious', 'q' and 'O' coils from Park's transformation. Out of these, 'O' coil (in which zero-sequence current io flows) has no coupling with the rotor coils and may be neglected if io = 0. Since the (transformed) mutual inductance terms between d, q coils and the rotor coils are constants, it can be interpreted that d and q coils rotate at the same speed as the rotor. Furthermore, as mutual inductances between the d-coil and the rotor coils on the q-axis are zero, it can be assumed that d-coil is aligned with the d-axis. Similarly, it can be assumed that q coil is aligned along with the q-axis. This is shown in Fig. 3.3.
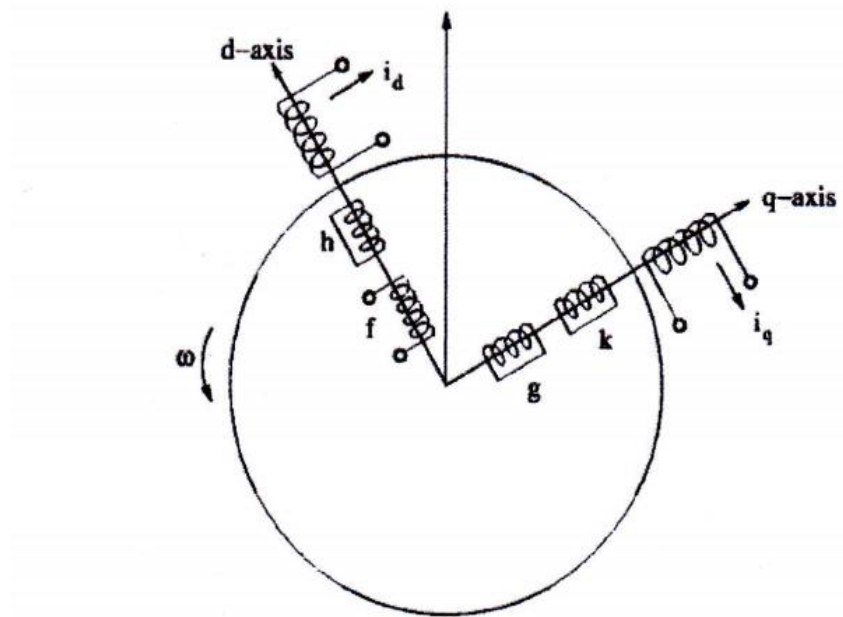
Fig 3.3: Synchronous Machine with rotating armature

3.3 Initial Condition Calculation:

To solve the nonlinear equations of the system we need to calculate the initial conditions based on the system operating point. Phasor diagram of the system described earlier is used to calculate the initial conditions.The phasor diagram is shown in figure 3.4.
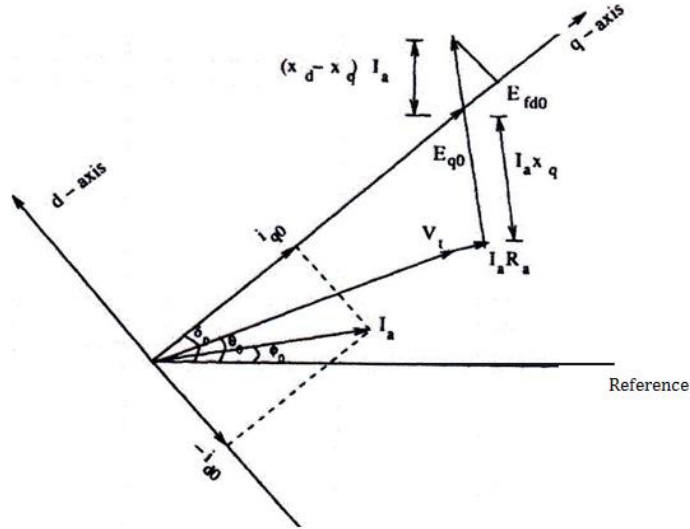
Fig 3.4: Phasor diagram of the system described earlier

The procedure of the initial condition computation is given below:

1) Compute i_{ao} from

$$\hat{I}_{ao} = I_{ao} < \phi_o = \frac{P_t - jQ_t}{V_{to} < -\theta_o}$$

2) Compute E_{qo} and σ_0 from

$$E_{qo} < \delta_o = V_{to} < \delta_o + (R_a + jx_q)I_{ao} < \phi_o$$

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3) Compute

$$i_{do} = -I_{ao} \sin(\delta_o - \phi_o)$$

$$i_{qo} = I_{ao} \cos(\delta_o - \phi_o)$$

$$v_{do} = -V_{to} \sin(\delta_o - \theta_o)$$

$$v_{qo} = V_{to} \cos(\delta_o - \theta_o)$$

4) Compute

$$E_{fdo} = E_{qo} - (x_d - x_q)i_{do}$$

$$E'_{qo} = E_{fdo} + (x_d - x'_d)i_{do}$$

$$E'_{do} = -(x_q - x'_q)i_{qo}$$

$$T_{eo} = E'_{qo}i_{qo} + E'_{do}i_{do} + (x'_d - x'_q)i_{do}i_{qo} = T_{mo}$$

3.4 Non-Linear Model for Synchronous Machine:

The system equations for a transient stability study are usually nonlinear. Magnetic saturation is either neglected or considered by using saturated values of mutual inductances X_{dc} (or Xad) and Xaq- The machine equations are, which denotes the states of the system,

$$\frac{d\delta}{dt} = \omega_b(S_m - S_{mo})$$

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

$$\frac{dE'_q}{dt} = \frac{1}{T'_{do}}\left[-E'_q + (x_d - x'_d)i_d + E_{fd}\right]$$

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

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The electrical torque T_e is expressed in terms of the state variables E_d' and E_q' and non-state variables i_d and i_q.

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

To guarantee superposition and homogeneity simultaneously we need to convert the nonlinear equations into linear equation. The knowledge of linearity will also help to design the controller. To convert the nonlinear equation Taylor series is used which is,

$$f(x) - f(x_o) \approx \frac{df}{dx}\bigg|_{x=x_o} (x - x_o)$$

3.5 Linear Model of Synchronous Machine:

By linearizing the nonlinear differential equations, the linearized model of the system is developed. The state space model has been used to study the system dynamic behavior described by the linear differential equations.The techniques of linear system analysis are used to study dynamic behavior of the system.The most common method of studying power system stability is to simulate each component by its transfer function.The various transfer function blocks are connected to represent the system under study. The system performance may then be analyzed by such methods as root-locus plots. Frequency domain analysis (Nyquist criteria), and Routh's criterion. The above methods have been frequently used in studies pertaining to small systems or a small number of machines.For larger systems the state-space model has been used more frequently in connection with system studies described by linear differential equations. Stability characteristics may be determined by examining the eigenvalues of the A matrix, where A is defined by the equation

$$\dot{x} = [A]x + [B]\left(\Delta V_{ref} + \Delta V_s\right)$$

$$x^t = [\Delta\delta \quad \Delta S_m \quad \Delta E_q' \quad \Delta E_{fd}]$$

$$[A] = \begin{bmatrix} 0 & \omega_B & 0 & 0 \\ -\dfrac{K_1}{2H} & -\dfrac{D}{2H} & -\dfrac{K_2}{2H} & 0 \\ -\dfrac{K_4}{T_{do}'} & 0 & -\dfrac{1}{T_{do}'K_3} & \dfrac{1}{T_{do}'} \\ -\dfrac{K_E K_5}{T_E} & 0 & -\dfrac{K_E K_6}{T_E} & -\dfrac{1}{T_E} \end{bmatrix}$$

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$$[B]^t = \begin{bmatrix} 0 & 0 & 0 & \dfrac{K_E}{T_E} \end{bmatrix}$$

Where x is an n vector denoting the states of the system and A is a coefficient matrix. The system inputs are represented by the vector $(\Delta V_{ref} + \Delta V_s)$ and these inputs are related mathematically to differential equations by an nX matrix B. This description has the advantage that A may be time varying and $(\Delta V_{ref} + \Delta V_s)$ may be used to represent several inputs if necessary.

$$\Delta \delta = \frac{\omega_B}{s} \Delta S_m = \frac{\omega_B}{s} \Delta \overline{\omega}$$

$$\Delta S_m = \frac{1}{2Hs} [\Delta T_m - \Delta T_e - D\Delta S_m]$$

$$T'_{do} \frac{d\Delta E'_q}{dt} = \Delta E_{fd} - \Delta E'_q + (x_d - x'_d)(C_1 \Delta \delta + C_2 \Delta E'_q)$$

Where,

$$\Delta T_e = K_1 \Delta \delta + K_2 \Delta E'_q$$

$$(1 + sT'_{do} K_3) \Delta E'_q = K_3 \Delta E_{fd} - K_3 K_4 \Delta \delta$$

$$\Delta V_t = K_5 \Delta \delta + K_6 \Delta E'_q$$

Let us consider the armature resistance are neglected, this refers to a lossless stator side. Using the above equations the block diagram of the excitation system is shown in Fig.3.5. The coefficients Kl to K6 are termed as Heffron-Phillips constants.They are dependent on the machine parameters and the operating conditions. Generally Kl, K2, K3 and K6 are positive. K4 is also mostly positive except for cases when Re is high. Ks can be either positive or negative. Ks are positive for low to medium external impedances (Re + jXe) and low to medium loadings.Ks are usually negative for moderate to high external impedances and heavy loadings. The expressions of constants K1-K6 are following:

$$K_1 = \frac{E_b E_{qo} \cos\delta_o}{(x_e + x_q)} + \frac{(x_q - x_d')}{(x_e + x_d')} E_b i_{qo} \sin\delta_o$$

$$K_2 = \frac{(x_e + x_q)}{(x_e + x_d')} i_{qo} = \frac{E_b \sin\delta_o}{(x_e + x_d')}$$

$$K_3 = \frac{(x_e + x_d')}{(x_d + x_e)}$$

$$K_4 = \frac{(x_d - x_d')}{(x_d' + x_e)} E_b \sin\delta_o$$

$$K_5 = -\frac{x_q v_{do} E_b \cos\delta_o}{(x_e + x_q) V_{to}} - \frac{x_d' v_{qo} E_b \sin\delta_o}{(x_e + x_d') V_{to}}$$

$$K_6 = \frac{x_e}{x_e + x_d'} \left(\frac{v_{qo}}{V_{to}}\right)$$
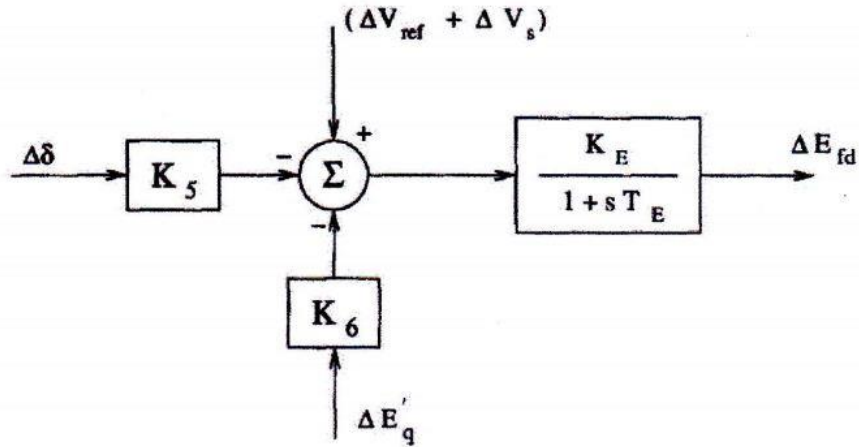
Fig 3.5: Excitation System block diagram

The system block diagram is obtained by combining the rotor swing equations, flux decay and excitation system. The overall block diagram is shown in Fig. 3.6. Here t h e damping term (D) i n the swing equations is neglected for convenience. (Actually D is generally small and neglecting it will give slightly pessimistic results).
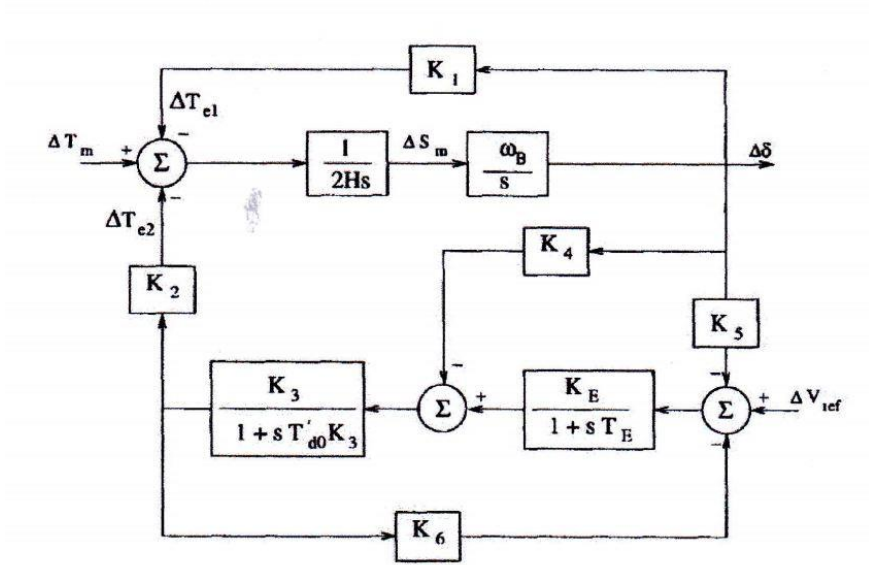
Fig3.6: Overall system block diagram

3.6 Automatic voltage Regulator:

The Automatic Voltage Regulator (AVR) maintains a constant or stable output voltage during operation, usually by varying the field voltage.Most AVR work automatically comparing the sensed voltage with the reference setting generator output voltage. Transient stability is improved by using automatic voltage regulator. In fault condition, field voltage is increased to keep generator voltage constant.

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3.7 Response attained by solving swing equation:

The solution of swing equation determines δ vs. t for a synchronous generator. Graph of the solution is known as swing curve. Inspection of swing curve will show whether the machines in a system will remain in synchronism after a disturbance. The computation of swing curves were carried over a period long enough to determine whether δ will increase without limit or reach a maximum and then start to decrease. The swing equations were solved by numerical method in MATLAB to find out the changes of accelerating power, rotor angle and angular velocity of rotor with respect to time.

3.8 Simulation Results:
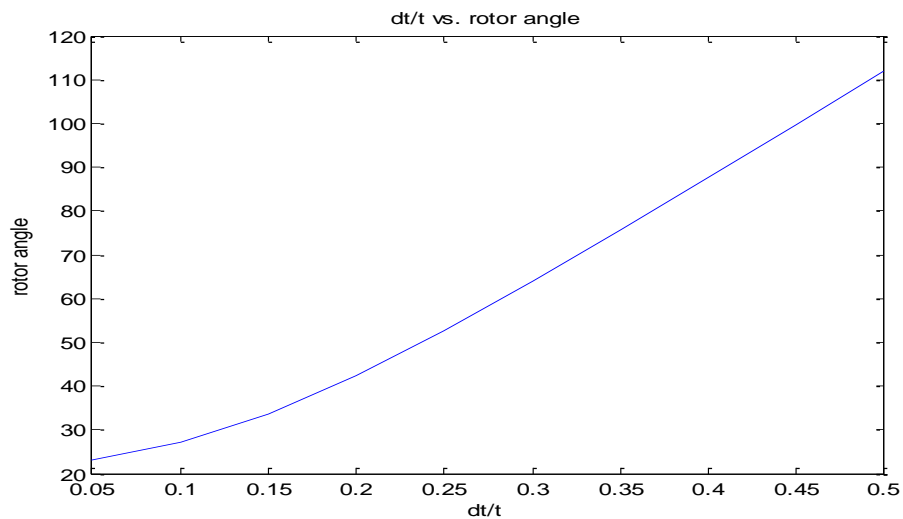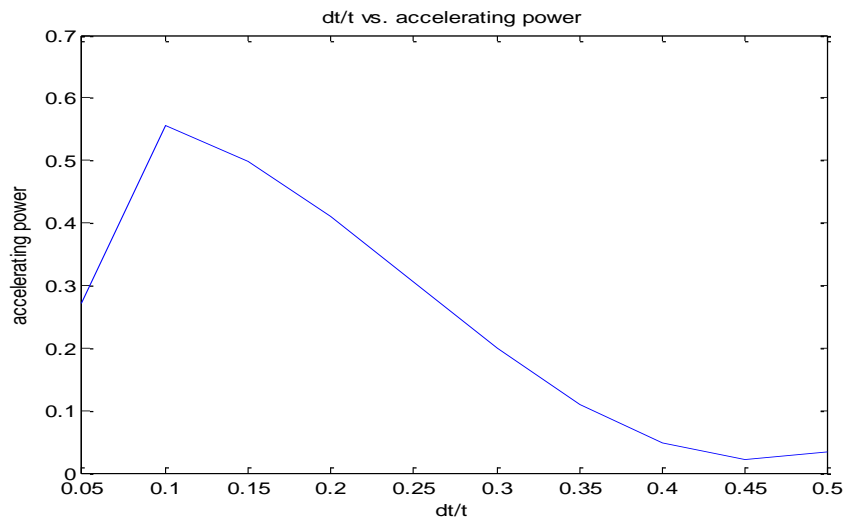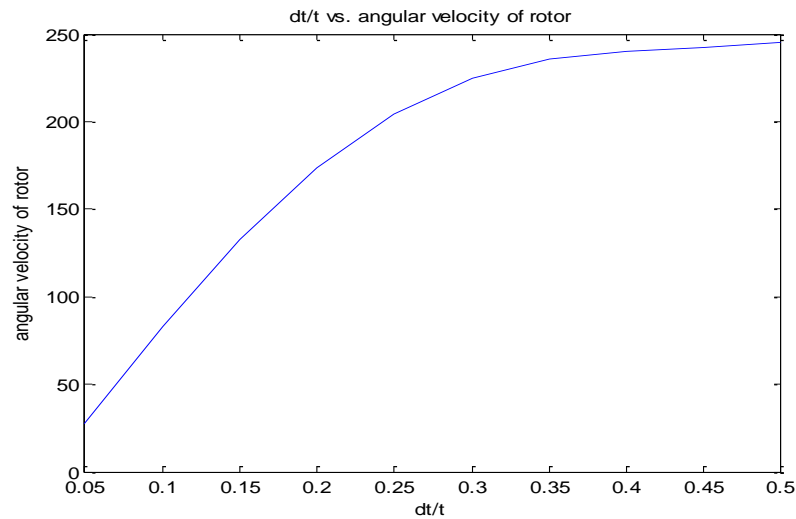
3.9 Calculation of Phillips Heffron Constants K_1 to K_6:

As the assumption of lossless network was imposed, for zero transmission line resistance the expressions for the constants K_1-K_6 were simplified. For transmission line reactance greater than zero, the constants K_1, K_2, K_3, K_4 and K_6 were positive. This was because δ_0 is generally less than 90 degree and iq_o is positive. K_6 is independent of the operating point and less than unity.

3.10 Simulation Results:

K_1=0.7750

K_2=1.0198

K_3=0.3600

K_4=1.3053

K_5=0.0500

K_6=0.4511

3.11 Plotting of Eigen value Loci for variation in P_g and xe: (Without AVR)

The complex pair of Eigen values corresponding to low frequency rotor oscillations were affected due to absence of AVR. For Pg=0.5 the damping is slightly increased with AVR while the frequency of the oscillation was slightly decreased. So while AVR can contribute damping torque, (with $K_5>0$) the synchronizing torque is slightly decreased.

3.12 Simulation Results:
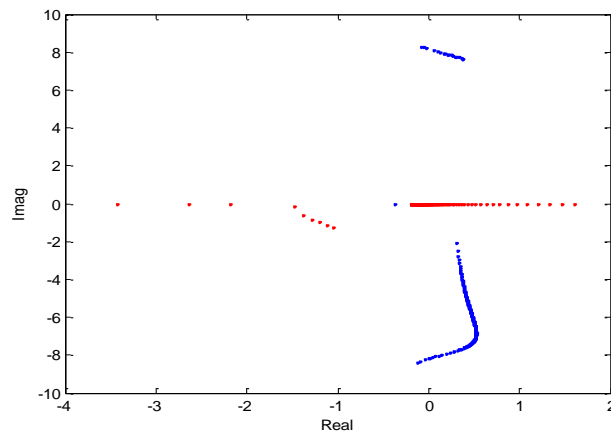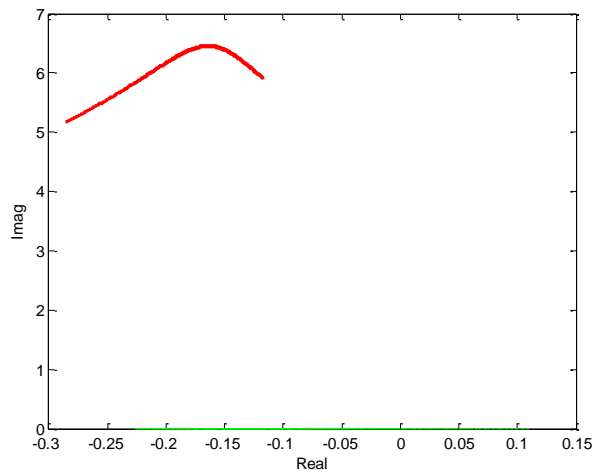
3.13 Plotting Eigen value Loci for variation in Ka (gain): (With AVR)

The loci of the critical Eigen values for P_g=1 p.u. showed that the damping started decreasing as AVR gain was increased from zero and the Eigen value crossed imaginary axis as Ka was increased beyond 17. The locus turned around as Ka was further increased and remained in the right half plane.

3.14 Simulation Result:
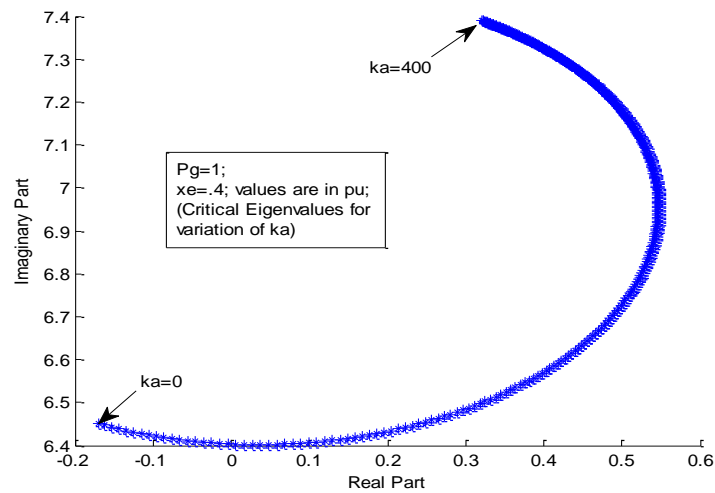
3.15 Discussion:

Condition for stability:
When AVR is not considered,

K1>0,
K1-K2K3K4>0
When AVR is considered, Ka<K4/-K5.

3.16 For Dynamic Behavior of system after switching:

The swing curves as well as the terminal voltages for four different cases are shown below in the simulation results. Here,

- The responses of the rotor angle were mainly oscillatory in all the cases. However, there was also a significant unidirectional component in the last case.
- The response of the terminal voltage had mainly a slowly varying unidirectional component in all the cases except the 3rd.
- While the rotor angle was reduced (in steady state) in all the cases, the terminal voltage was reduced in 1st and 3rd cases while increased in 2nd and 4th following the switching disturbance of duration 0.001s.
- Q_t was increased as the reactance was reduced, since E_{fd} remained at the same level as before. With positive Q_t, the increase in Q_t had the effect of reducing the terminal voltage while with negative Q_t, the opposite was true.

3.17 Simulation Result:

Pt=.9(pu), Qt=.6(pu)

δ **vs. t**

Variation of rotor angle(degree) w.r.t. time (sec)

Vt vs. t

Variation of terminal voltage(pu) w.r.t. time(sec)

Pt=.9(pu), Qt=-.02(pu)

δ **vs t**

Variation of rotor angle(degree) w.r.t. time (sec)

Vt vs. t

Variation of terminal voltage(pu) w.r.t. time(sec)

Pt=.3(pu), Qt=.02(pu)

$\delta\ vs.\ t$

Variation of rotor angle(degree) w.r.t. time (sec)

Vt vs. t

Variation of terminal voltage(pu) w.r.t. time(sec)
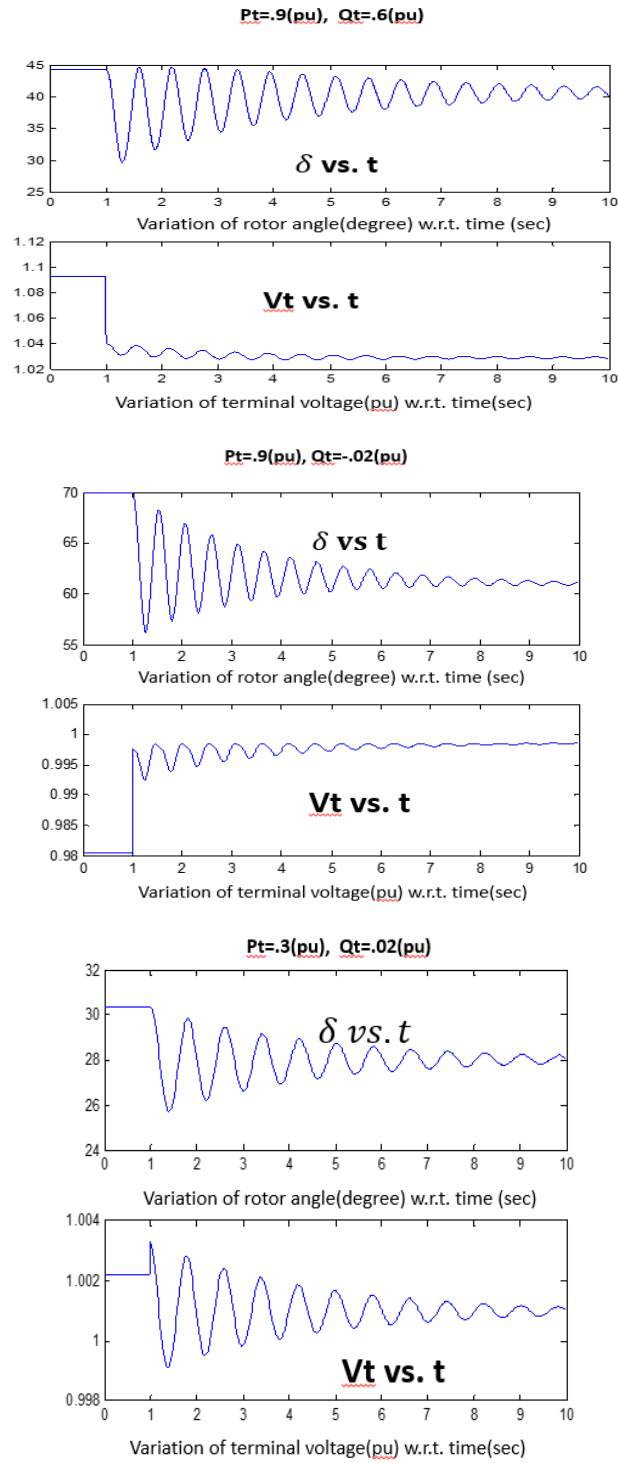
Chapter 4
Wind Profile

4.1 Wind Profile Simulation:

Wind speed changes continuously and its magnitude is random over any interval. For modeling of wind profile wind speed is considered constant for some intervals and the fluctuations during such interval is considered to be combination of constant sinusoidal variations.

Formula used for the simulation: [1]

$$V_\omega = V_m[1 - .2\cos(\frac{2\pi t}{20}) - .5\cos(\frac{2\pi t}{600})]$$

4.2 Simulation Result:

Wind speed(m/s) vs. Time(s)
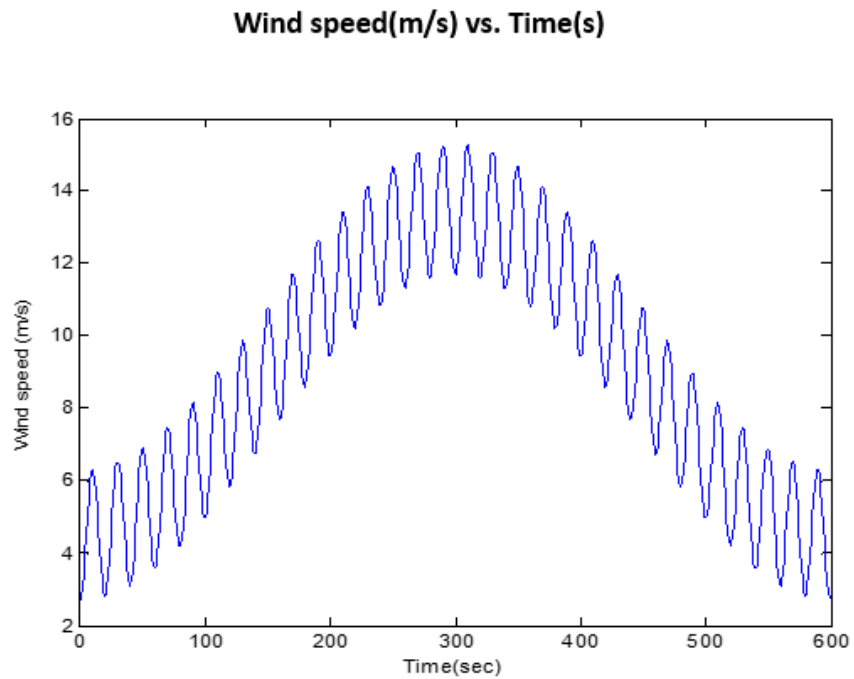
4.3 Power coefficient versus tip speed ratio curve simulation:

Simulated model equations [1]:

$$P_m = \frac{1}{2} \rho A C_p (V_w)^3$$

$$\lambda = \frac{\Omega R}{V_w}$$

$$C_p(\lambda, \beta) = 0.5176 \left(\frac{116}{\lambda_i} - 0.4\beta - 5 \right) e^{-\frac{21}{\lambda_i}} + .0168\lambda$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}$$

Here, ρ is air density and A is the swept area by the turbine blades. The power co-efficient Cp depends on both the blade pitch angle Beta and tip speed ratio Lambda. R is the wind turbine rotor radius, omega is the mechanical angular velocity.

4.4 Simulation Result:

Power Coefficient vs. tip speed ratio
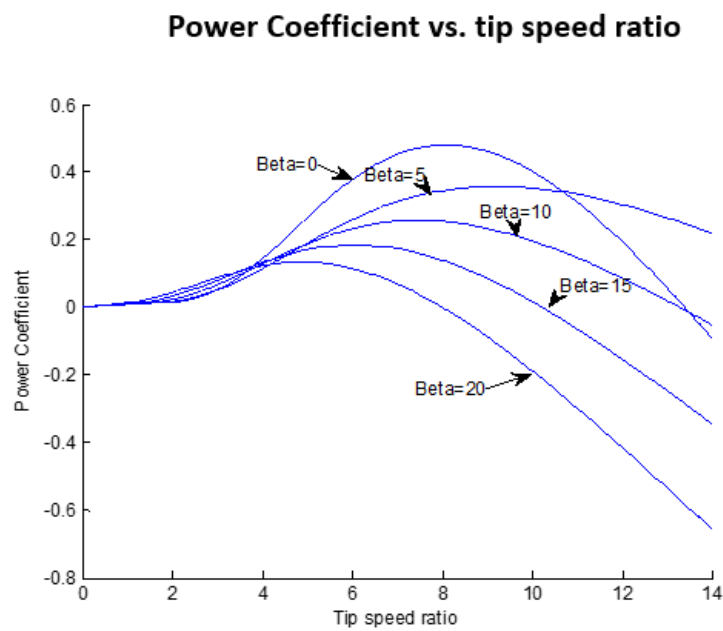
Turbine power output(pu) vs. Turbine speed(pu)
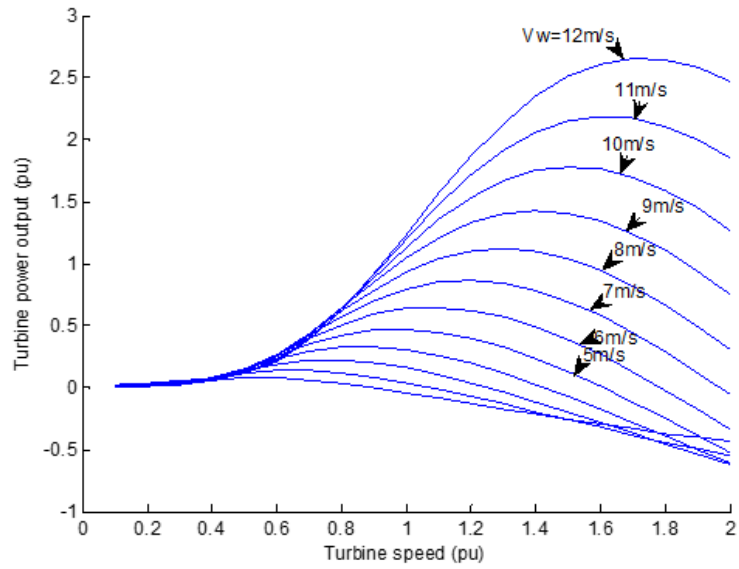
Chapter 5
Fixed speed Induction Generator Modelling

5.1 Simulated Model Equation [1] :

$$\dot{\omega} = \frac{1}{2H}[T_m - T_e]$$

$$\dot{e}'_q = -\frac{1}{T'_o}\left[e'_q + (x_s - x')i_{ds}\right] - s\omega_b e'_d + \frac{x_m}{x_{rr}}\omega v_{dr}$$

$$\dot{e}'_d = -\frac{1}{T'_o}\left[e'_d - (x_s - x')i_{qs}\right] + s\omega_b e'_q - \frac{x_m}{x_{rr}}\omega_b v_{qr}$$

$$i_{qs} = -\omega_d i_{ds} - \frac{1}{x'}\left[\frac{1}{T'_o}(x_s - x') + \omega_b R_s\right]i_{qs} + \frac{1}{T'_o x'}e'_d$$
$$+ (1-s)\frac{\omega_e}{x'}e'_q - \frac{\omega_b}{x'}v_{qs} + \frac{x_m \omega_b}{x_r x'}v_{qr}$$

$$i_{ds} = -\frac{1}{x'}\left[\frac{1}{T'_o}(x_s - x') + \omega_b R_s\right]i_{ds} + \omega_e i_{qs}$$
$$+ (1-s)\frac{\omega_e}{x'}e'_d - \frac{1}{T'_o x'}e'_q - \frac{\omega_b}{x'}v_{ds} + \frac{x_m \omega_b}{x_r x'}v_{dr}$$

5.2 Non-Linear Model Simulation based on wind profile: (without any disturbance)

- States representing the system are : [i_{ds} i_{qs} e_d e'_q ω]

- Initial conditions were calculated using fsolve-built in function of MATLAB. For this the steady state operating point was achieved after a certain period in the curves.

- Using these initial values of state variables, the response was observed when the nonlinear system under consideration is subjected to an input side disturbance of duration 0.1 second.

- Euler's method for solving differential equations was used for this purpose.

5.3 Simulation Results: (Without any disturbance- Steady state)
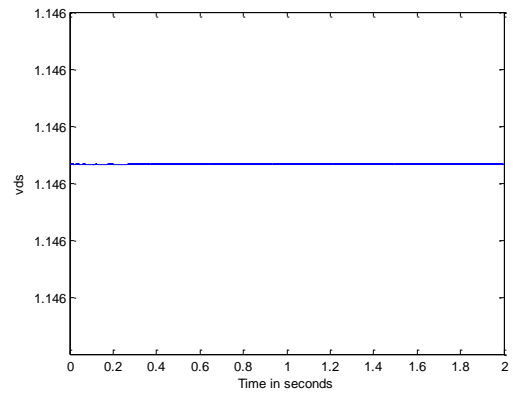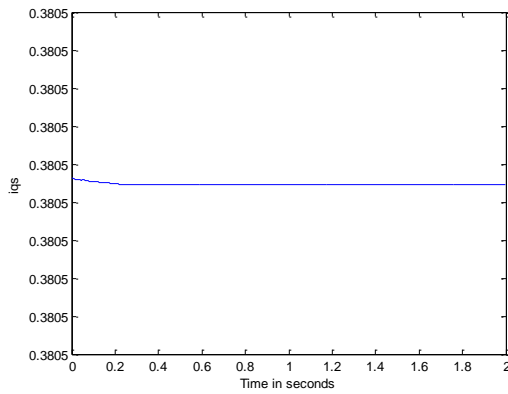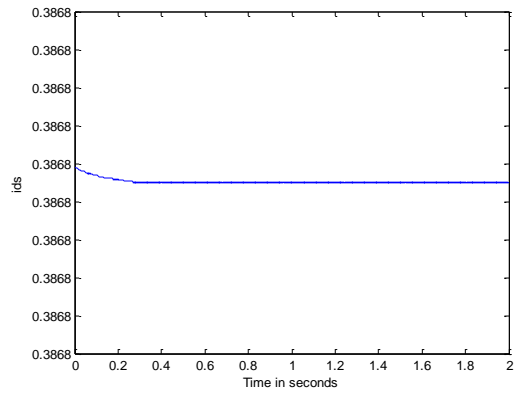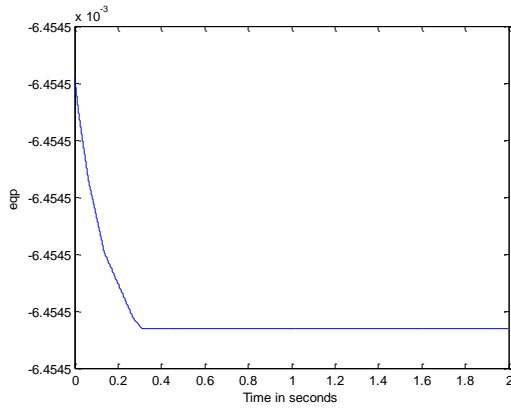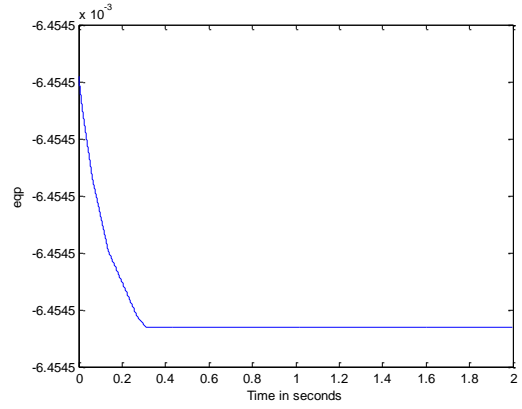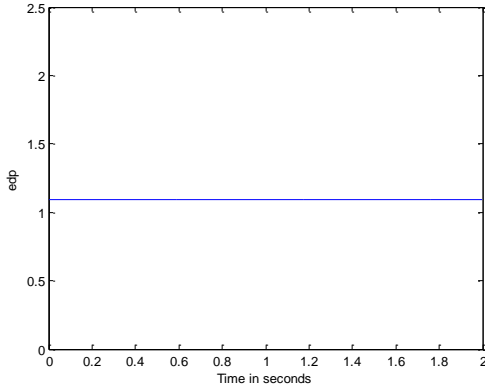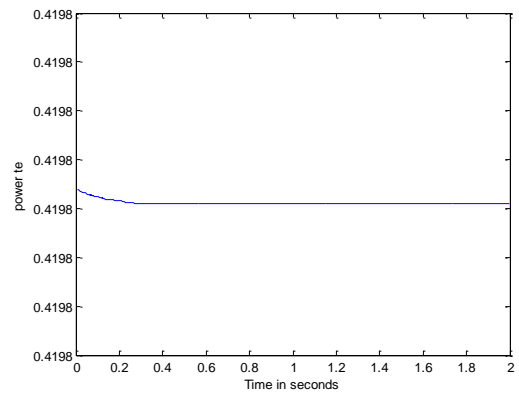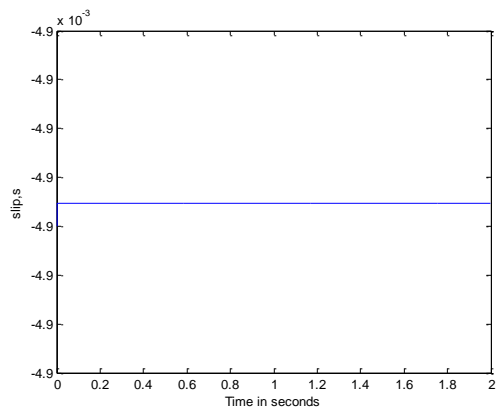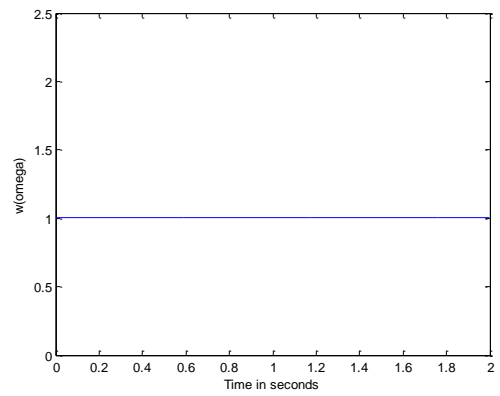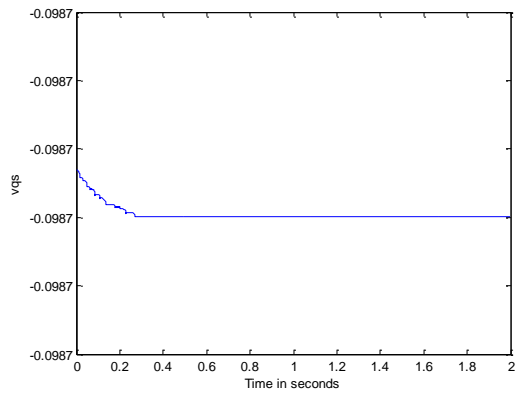
5.4 Simulation Results: (after giving turbine side disturbance of 0.1 seconds)
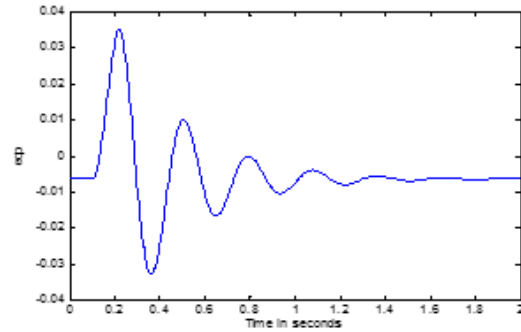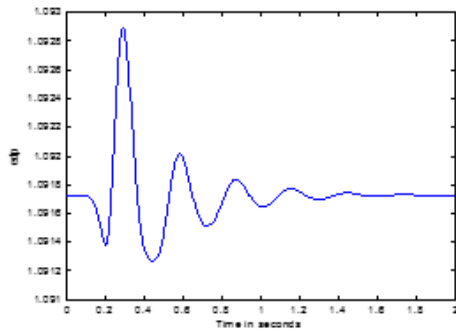
edp,eqp & vds vs. t
in clockwise order

iqs, vds & vqs vs. t
in clockwise order

45
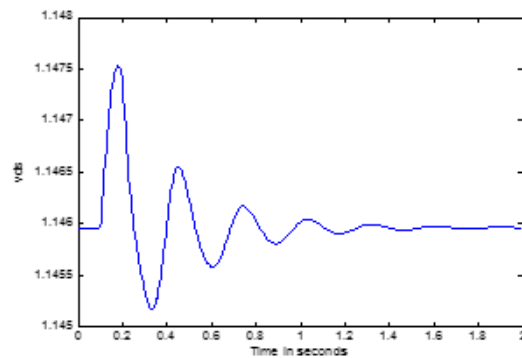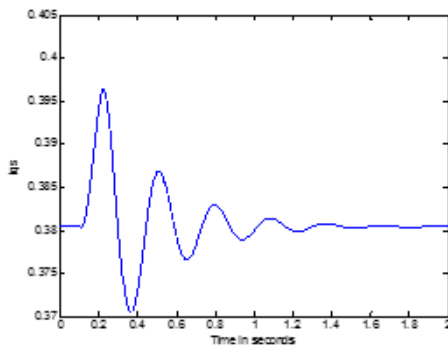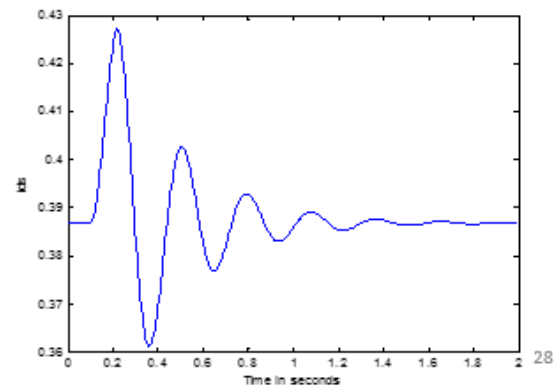
w, s & te vs. t in clockwise order
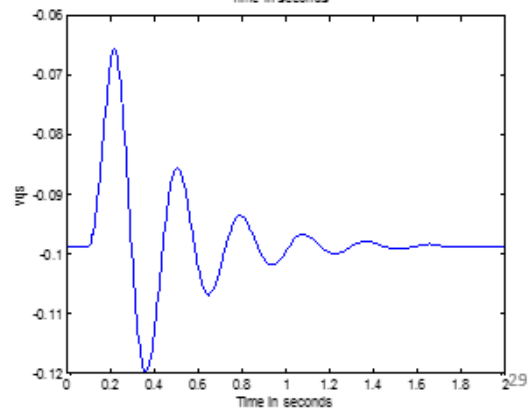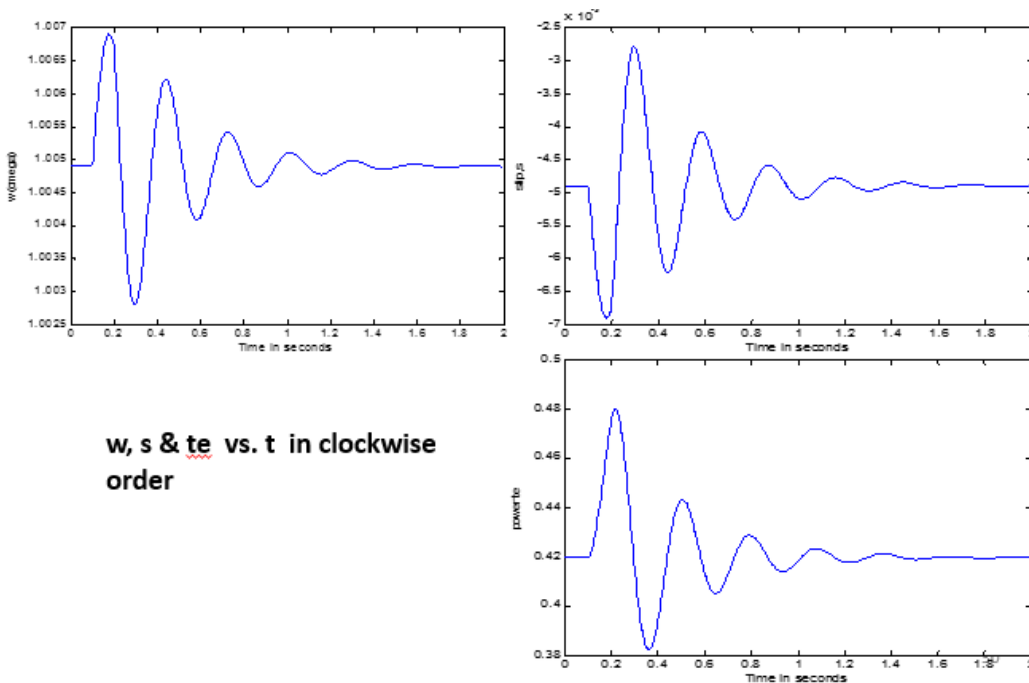
5.5 Linear approximation of Non-Linear Model Simulation based on wind profile:

- ✓ Eigen value was calculated using the state space model.[1]
- ✓ From the left and right Eigen vectors participation factor of individual states in different modes was calculated and critical Eigen value was found.
- ✓ Participation factors were normalized.
- ✓ Stability of the system in the case of linear approximation was observed by varying 3 network parameters. [1]

5.6 Simulation Results:

Ids_0= .3868 $\quad\quad$ edp_0= 1.0917 $\quad\quad$ vds_0=1.1460 $\quad\quad$ w_0=1.0049

Iqs_0= .3805 $\quad\quad$ eqp_0= -.0065 $\quad\quad$ vqs_0=-.0987

5.8 Analysis of System Instability:

To determine effective controller for a system to enhance its stability it is very important to diagnose the critical mode i.e. mode responsible for initiating system instability [1]. Degree of coupling between different modes, and the role of each modes were observed by examining Eigen values for different transmission line reactances, load susceptances and generator rotor inertia constants. When the critical Eigen value loci moves away from imaginary axis in the direction of negative real axis with increasing loading, we can say that system is becoming more stable. On the contrary, when with increasing loading, the critical Eigen value loci moves towards the imaginary axis, we can say that the system is on the verge of becoming unstable; with potential possibility of instability with increased loading. For 3 different parameters' variations, the critical Eigen value loci was taken under consideration.

5.7 Simulation of Critical Eigen Values' loci for variation of Line reactance:

The considered line reactances were from 0.1 to 1.0 p.u. The critical Eigen value locus moved away from imaginary axis with increasing line reactance. The values close to the imaginary axis were zoomed to show the distinct locus of the Eigen values.

5.8 Tabulation of Normalized participation factors of individual states in different modes:

For x=.1

	Edp	Eqp	ids	Iqs	ω
Mode1	0.0133	0.0133	0.9172	0.0589	0.0589
Mode2	0.0134	0.0134	0.0137	0.4782	0.4782
Mode3	0.4875	0.4875	0.0047	0.0123	0.0123
Mode4	0.4843	0.4843	0.0050	0.0122	0.0122
Mode5	0.0014	0.0014	0.0595	0.4383	0.4383

For x=.2

	Edp	Eqp	ids	Iqs	ω
Mode1	0.0079	0.0079	0.9668	0.0348	0.0348
Mode2	0.0079	0.0079	0.0049	0.4878	0.4878
Mode3	0.4927	0.4927	0.0011	0.0078	0.0078
Mode4	0.4906	0.4906	0.0027	0.0070	0.0070
Mode5	0.0009	0.0009	0.0244	0.4625	0.4625

For x=.3

	Edp	Eqp	Ids	Iqs	ω
Mode1	0.0048	0.0048	0.9764	0.0231	0.0231
Mode2	0.0049	0.0049	0.0111	0.4923	0.4923
Mode3	0.4955	0.4955	0.0000	0.0054	0.0054
Mode4	0.4941	0.4941	0.0019	0.0044	0.0044
Mode5	0.0007	0.0007	0.0106	0.4748	0.4748

For x=.4

	Edp	Eqp	Ids	Iqs	ω
Mode1	0.0031	0.0031	0.9826	0.0163	0.0163
Mode2	0.0031	0.0031	0.0106	0.4971	0.4971
Mode3	0.4971	0.4971	0.0003	0.0040	0.0040
Mode4	0.4961	0.4961	0.0015	0.0030	0.0030
Mode5	0.0005	0.0005	0.0050	0.4823	0.4823

For x=.5

	Edp	Eqp	Ids	Iqs	ω
Mode1	0.0014	0.0014	0.9928	0.0087	0.0087
Mode2	0.0014	0.0014	0.0042	0.4937	0.4937
Mode3	0.4987	0.4987	0.0003	0.0026	0.0026
Mode4	0.4981	0.4981	0.0011	0.0017	0.0017
Mode5	0.0003	0.0003	0.0015	0.4932	0.4932

For x=.7

	Edp	Eqp	Ids	Iqs	ω
Mode1	0.0010	0.0010	0.9791	0.0116	0.0116
Mode2	0.0010	0.0010	0.0187	0.4886	0.4886
Mode3	0.4991	0.4991	0.0002	0.0023	0.0023
Mode4	0.4986	0.4986	0.0010	0.0014	0.0014
Mode5	0.0002	0.0002	0.0010	0.4961	0.4961

For x=.8

	Edp	Eqp	Ids	Iqs	ω
Mode1	0.0008	0.0008	0.9594	0.0202	0.0202
Mode2	0.0008	0.0008	0.0388	0.4793	0.4793
Mode3	0.4993	0.4993	0.0001	0.0020	0.0020
Mode4	0.4990	0.4990	0.0009	0.0012	0.0012
Mode5	0.0002	0.0002	0.0007	0.4973	0.4973

For x=.9

	Edp	Eqp	Ids	Iqs	ω
Mode1	0.0006	0.0006	0.9331	0.0331	0.0331
Mode2	0.0006	0.0006	0.0654	0.4663	0.4663
Mode3	0.4995	0.4995	0.0001	0.0017	0.0017
Mode4	0.4992	0.4992	0.0008	0.0010	0.0010
Mode5	0.0001	0.0001	0.0006	0.4979	0.4979

For x=1

	Edp	Eqp	Ids	Iqs	ω
Mode1	0.0004	0.0004	0.8987	0.0501	0.0501
Mode2	0.0004	0.0004	0.0999	0.4493	0.4493
Mode3	0.4996	0.4996	0.0000	0.0016	0.0016
Mode4	0.4994	0.4994	0.0008	0.0008	0.0008
Mode5	0.0001	0.0001	0.0006	0.4982	0.4982

5.9 Simulation Results:

**Plotting of Critical Eigen Values for
variation of line reactance from 0.1 to 1.0**
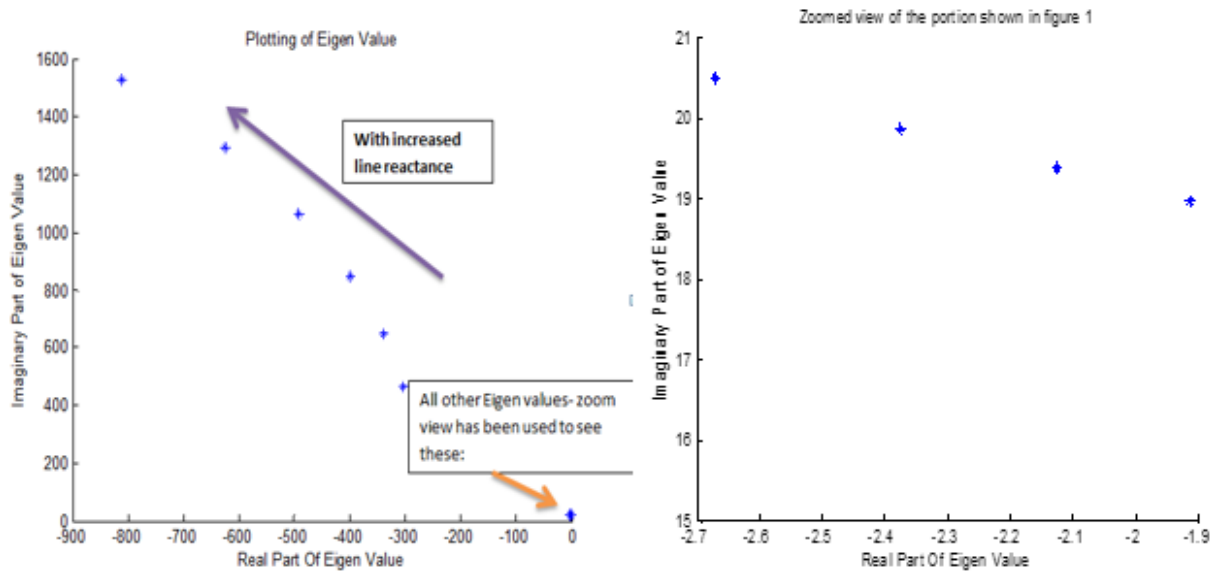
5.10 Relative Participation factors at different modes: (in Bar plots)
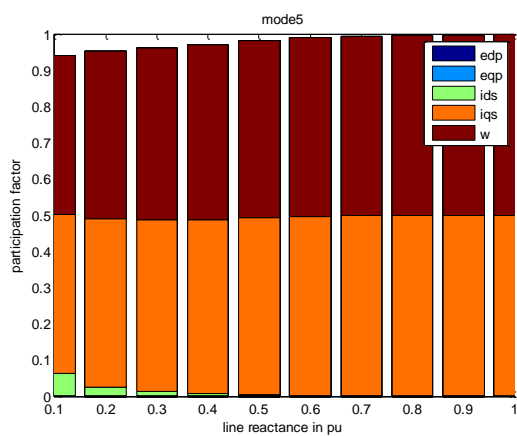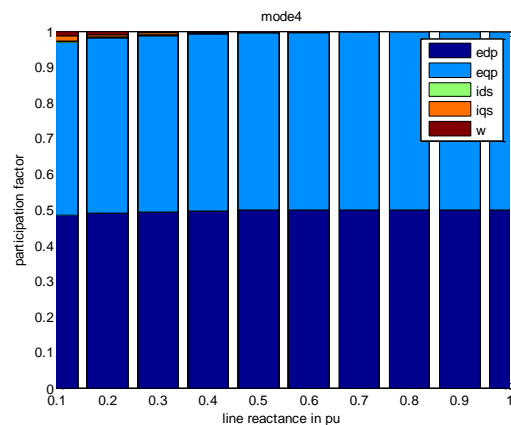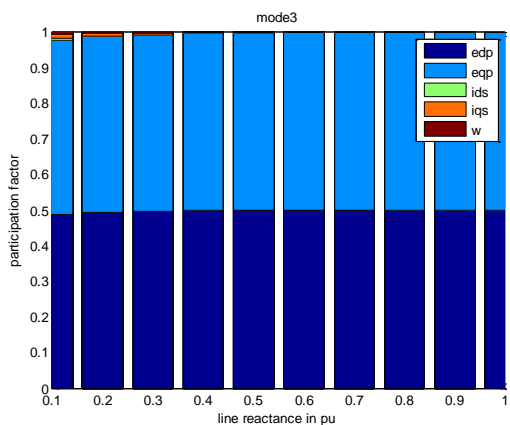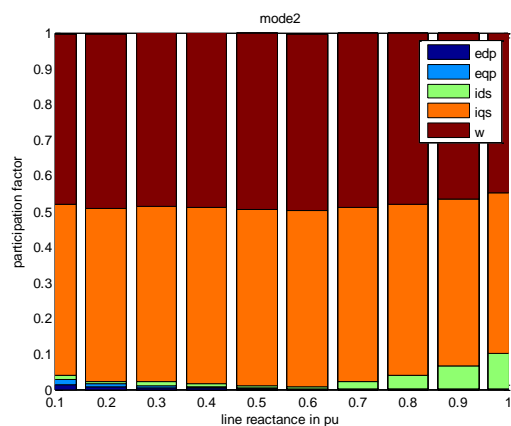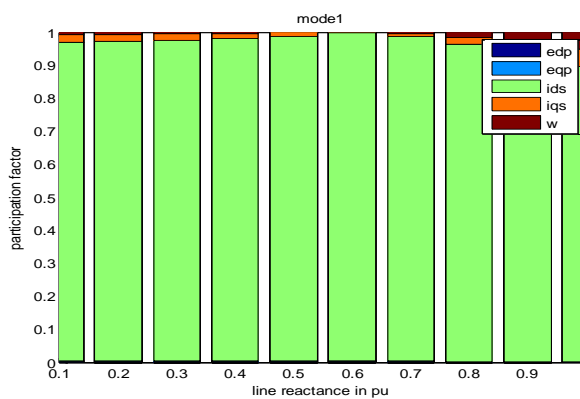
5.11 Simulation of Critical Eigen Values' loci for variation of Load Susceptance:

The considered load susceptances were from 0.1 to 1.0 p.u. The critical Eigen value locus moved away from imaginary axis with increasing load susceptance. The values close to the imaginary axis were zoomed to show the distinct locus of the Eigen values.

5.12 Tabulation of Normalized participation factors of individual states in different modes:

For b11=.1

	edp	edq	ids	iqs	ω
Mode1	0.0028	0.0028	0.9644	0.0232	0.0232
Mode2	0.0028	0.0028	0.0291	0.4973	0.4973
Mode3	0.4973	0.4973	0.0000	0.0023	0.0023
Mode4	0.4969	0.4969	0.0011	0.0025	0.0025
Mode5	0.0003	0.0003	0.0054	0.4748	0.4748

For b11=.2

	edp	edq	ids	iqs	ω
Mode1	0.0023	0.0023	0.9704	0.0194	0.0194
Mode2	0.0023	0.0023	0.0244	0.4970	0.4970
Mode3	0.4978	0.4978	0.0002	0.0024	0.0024
Mode4	0.4973	0.4973	0.0011	0.0023	0.0023
Mode5	0.0003	0.0003	0.0039	0.4788	0.4788

For b11=.3

	edp	edq	ids	iqs	ω
Mode1	0.0023	0.0023	0.9704	0.0194	0.0194
Mode2	0.0023	0.0023	0.0244	0.4970	0.4970
Mode3	0.4978	0.4978	0.0002	0.0024	0.0024
Mode4	0.4973	0.4973	0.0011	0.0023	0.0023
Mode5	0.0003	0.0003	0.0039	0.4788	0.4788

For b11=.4;

	edp	edq	ids	iqs	ω
Mode1	0.0021	0.0021	0.9759	0.0166	0.0166
Mode2	0.0021	0.0021	0.0196	0.4968	0.4968
Mode3	0.4980	0.4974	0.0002	0.0025	0.0025
Mode4	0.4974	0.4974	0.0012	0.0022	0.0022
Mode5	0.0003	0.0003	0.0032	0.4819	0.4819

For b11=.5

	edp	edq	ids	iqs	ω
Mode1	0.0019	0.0019	0.9838	0.0130	0.0130
Mode2	0.0019	0.0019	0.0122	0.4962	0.4962
Mode3	0.4982	0.4982	0.0003	0.0027	0.0027
Mode4	0.4976	0.4976	0.0012	0.0021	0.0021
Mode5	0.0003	0.0003	0.0026	0.4860	0.4860

For b11=.6

	edp	edq	ids	iqs	ω
Mode1	0.0017	0.0017	0.9953	0.0096	0.0096
Mode2	0.0017	0.0017	0.0012	0.4947	0.4947
Mode3	0.4984	0.4984	0.0003	0.0029	0.0029
Mode4	0.4978	0.4978	0.0012	0.0019	0.0019
Mode5	0.0003	0.0003	0.0020	0.4909	0.4909

For b11=.7

	edp	edq	ids	iqs	ω
Mode1	0.0015	0.0015	0.9825	0.0108	0.0108
Mode2	0.0015	0.0015	0.0146	0.4898	0.4898
Mode3	0.4986	0.4986	0.0003	0.0031	0.0031
Mode4	0.4980	0.4980	0.0018	0.0018	0.0018
Mode5	0.0003	0.0003	0.4945	0.4945	0.4945

For b11=.8

	edp	edq	ids	iqs	ω
Mode1	0.0013	0.0013	0.9614	0.0193	0.0193
Mode2	0.0013	0.0013	0.0361	0.4798	0.4798
Mode3	0.4988	0.4988	0.0003	0.0033	0.0033
Mode4	0.4981	0.4981	0.0012	0.0016	0.0016
Mode5	0.0003	0.0003	0.0009	0.4960	0.4960

For b11=.9

	edp	edq	ids	iqs	ω
Mode1	0.0012	0.0012	0.9326	0.0333	0.0333
Mode2	0.0012	0.0012	0.0654	0.4652	0.4652
Mode3	0.4990	0.4990	0.0003	0.0036	0.0036
Mode4	0.4983	0.4983	0.0011	0.0014	0.0014
Mode5	0.0004	0.0004	0.0005	0.4965	0.4965

For b11=1;

	edp	edq	ids	iqs	ω
Mode1	0.0010	0.0010	0.8938	0.0528	0.0528
Mode2	0.0010	0.0010	0.1046	0.4454	0.4454
Mode3	0.4992	0.4992	0.0003	0.0039	0.0039
Mode4	0.4984	0.4984	0.0010	0.0013	0.0013
Mode5	0.0004	0.0004	0.0002	0.4967	0.4967

5.13 Simulation Result:

Plotting of Critical Eigen Values for variation of load Susceptance from 0.1to 1.0(p.u)
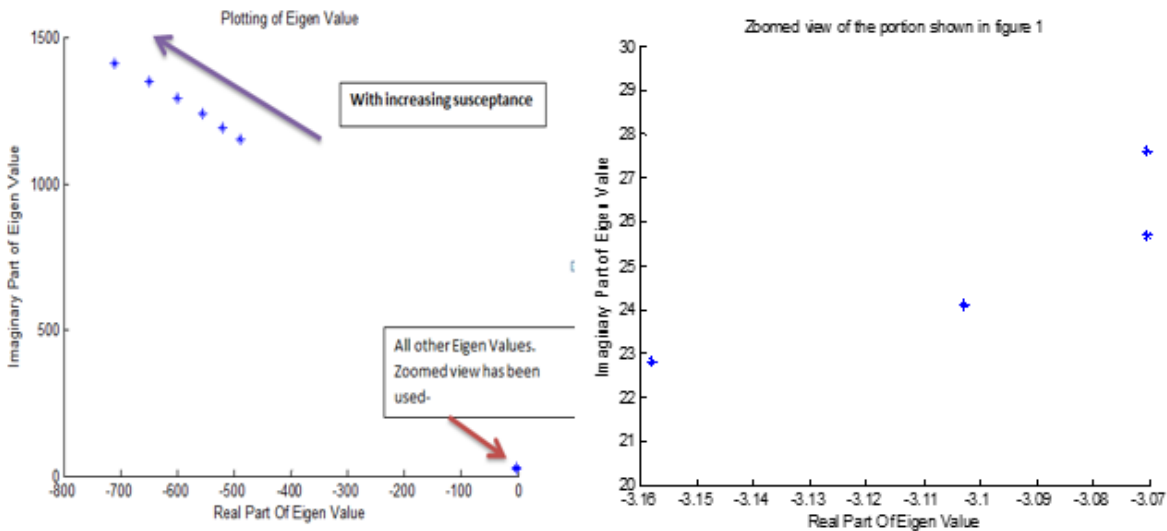
5.14 Relative Participation factors at different modes: (in Bar plots)
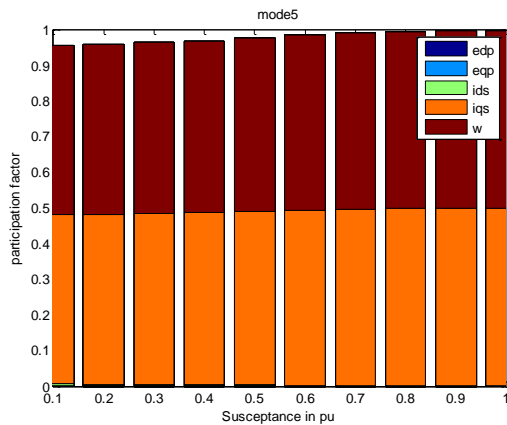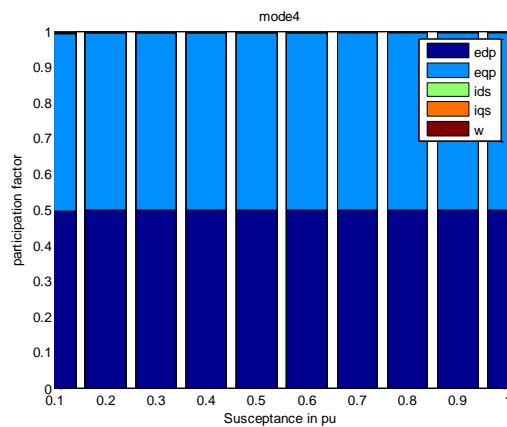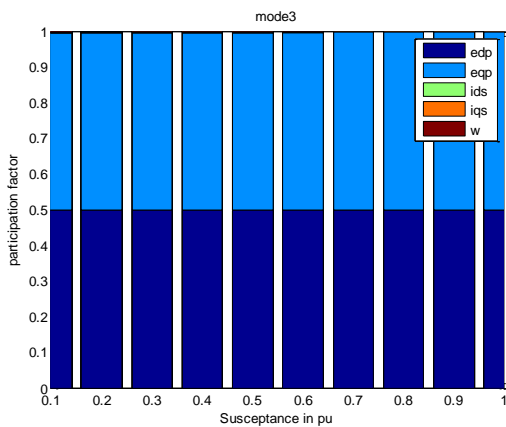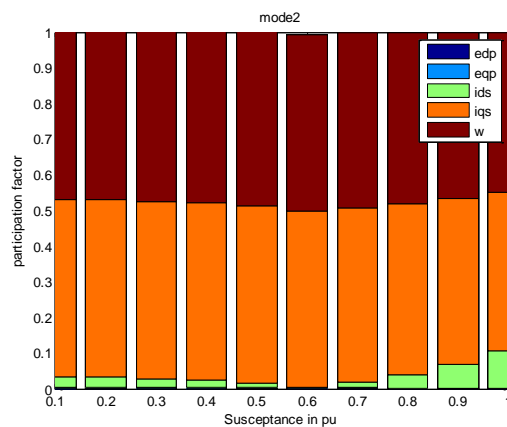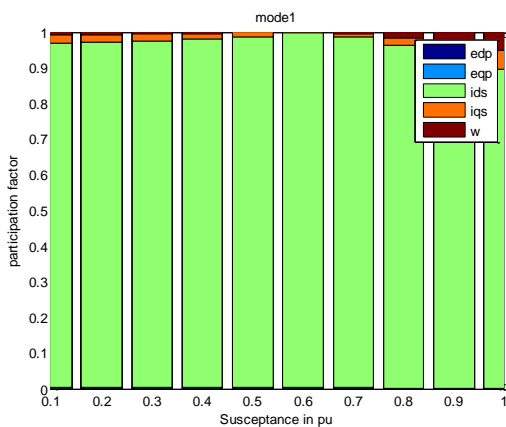
5.15 Simulation of Critical Eigen Values' loci for variation of Generator inertia constant:

The considered rotor inertia constants were from 0.1 to 1.0 p.u. The critical Eigen value locus moved towards the imaginary axis with increasing inertia constants.

5.16 Tabulation of Normalized participation factors of individual states in different modes:

For hg=.1,

	Edp	Eqp	Ids	Iqs	ω
Mode 1	0.0017	0.0017	0.9920	0.0049	0.0049
Mode 2	0.0016	0.0016	0.0061	0.4950	0.4950
Mode 3	0.4986	0.4986	0.0004	0.0060	0.0060
Mode 4	0.4964	0.4964	0.0012	0.0045	0.0045
Mode 5	0.0016	0.0016	0.0004	0.4896	0.4896

For hg=.2,

	Edp	Eqp	Ids	Iqs	ω
Mode 1	0.0017	0.0017	0.9929	0.0064	0.0064
Mode 2	0.0017	0.0017	0.0048	0.4954	0.4954
Mode 3	0.4985	0.4985	0.0003	0.0043	0.0043
Mode 4	0.4973	0.4973	0.0012	0.0031	0.0031
Mode 5	0.0008	0.0008	0.0008	0.4907	0.4907

For hg=.3,

	Edp	Eqp	Ids	Iqs	ω
Mode 1	0.0017	0.0017	0.9937	0.0077	0.0077
Mode 2	0.0017	0.0017	0.0036	0.4953	0.4953
Mode 3	0.4985	0.4985	0.0003	0.0036	0.0036
Mode 4	0.4976	0.4976	0.0012	0.0025	0.0025
Mode 5	0.0005	0.0005	0.0012	0.4910	0.4910

For hg=.4,

|	Edp	Eqp	Ids	Iqs	ω
Mode 1	0.0017	0.0017	0.9945	0.0087	0.0087
Mode 2	0.0017	0.0017	0.0024	0.4950	0.4950
Mode 3	0.4984	0.4984	0.0003	0.0032	0.0032
Mode 4	0.4977	0.4977	0.0012	0.0022	0.0022
Mode 5	0.0004	0.0004	0.0016	0.4909	0.4909

For hg=.5,

	Edp	Eqp	Ids	Iqs	ω
Mode 1	0.0017	0.0017	0.9953	0.0096	0.0096
Mode 2	0.0017	0.0017	0.0012	0.4947	0.4947
Mode 3	0.4984	0.4984	0.0003	0.0029	0.0029
Mode 4	0.4978	0.4978	0.0012	0.0019	0.0019
Mode 5	0.0003	0.0003	0.0020	0.4909	0.4909

For hg=.6,

	Edp	Eqp	Ids	Iqs	ω
Mode 1	0.0017	0.0017	0.9961	0.0105	0.0105
Mode 2	0.0017	0.0017	0.0000	0.4944	0.4944
Mode 3	0.4984	0.4984	0.0003	0.0027	0.0027
Mode 4	0.4978	0.4978	0.0012	0.0018	0.0018
Mode 5	0.0003	0.0003	0.0024	0.4907	0.4907

For hg=.7,

	Edp	Eqp	Ids	Iqs	ω
Mode 1	0.0017	0.0017	0.9946	0.0112	0.0112
Mode 2	0.0017	0.0017	0.0112	0.4941	0.4941
Mode 3	0.4984	0.4984	0.0003	0.0025	0.0025
Mode 4	0.4979	0.4979	0.0112	0.0016	0.0016
Mode 5	0.0002	0.0002	0.0028	0.4906	0.4906

For hg=.8,

	Edp	Eqp	Ids	Iqs	ω
Mode 1	0.0017	0.0017	0.9931	0.0119	0.0119
Mode 2	0.0017	0.0017	0.0023	0.4938	0.4938
Mode 3	0.4984	0.4984	0.0003	0.0024	0.0024
Mode 4	0.4979	0.4979	0.0012	0.0015	0.0015
Mode 5	0.0002	0.0002	0.0031	0.4904	0.4904

For hg=.9,

	Edp	Eqp	Ids	Iqs	ω
Mode 1	0.0017	0.0017	0.9916	0.0126	0.0126
Mode 2	0.0018	0.0018	0.0034	0.4935	0.4935
Mode 3	0.4984	0.4984	0.0003	0.0023	0.0023
Mode 4	0.4979	0.4979	0.0012	0.0014	0.0014
Mode 5	0.0002	0.0002	0.0035	0.4903	0.4903

For hg=1.0,

	Edp	Eqp	Ids	Iqs	ω
Mode 1	0.0017	0.0017	0.9901	0.0132	0.0132
Mode 2	0.0018	0.0018	0.0045	0.4932	0.4932
Mode 3	0.4984	0.4984	0.0002	0.0022	0.0022
Mode 4	0.4980	0.4980	0.0012	0.0014	0.0014
Mode 5	0.0002	0.0002	0.0039	0.4901	0.4901

## 5.17 Simulation Result:

Plotting of Critical Eigen Values for variation of Rotor inertia constant from 0.1to 1.0(p.u)
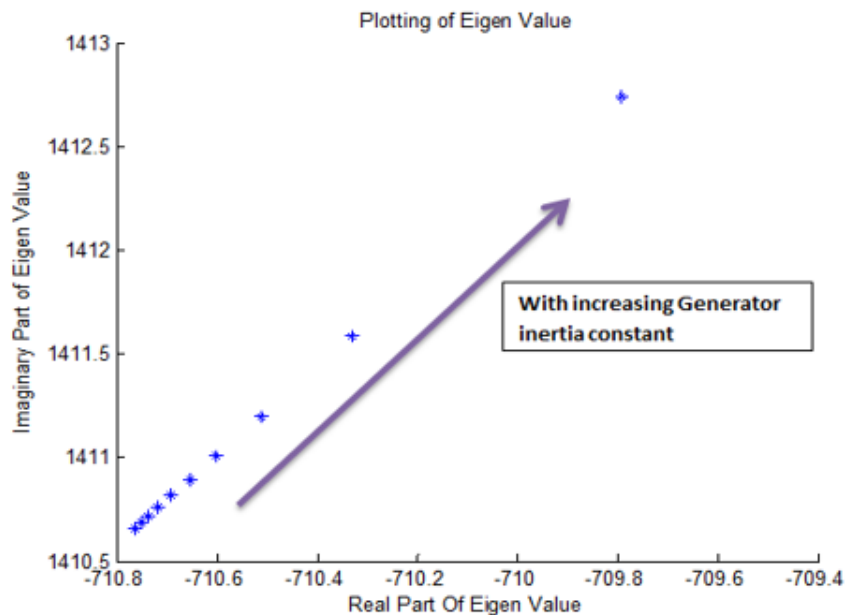
# 5.18 Relative Participation factors at different modes: (in Bar plots)
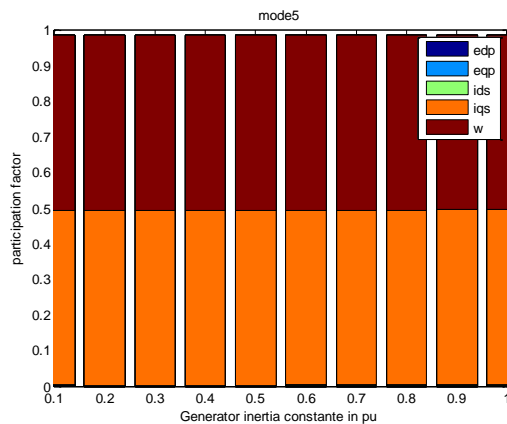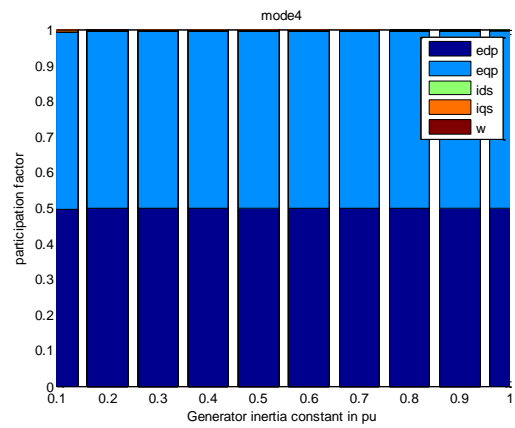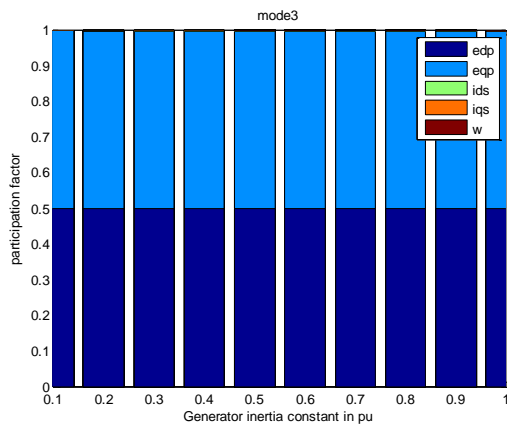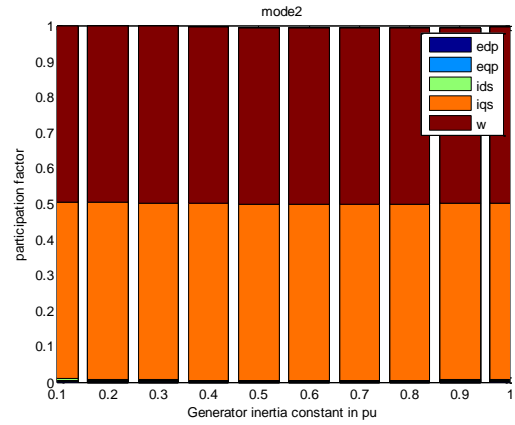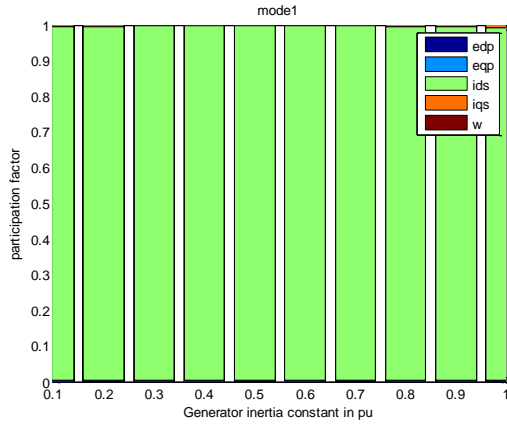
5.19 Discussion:

❑ For the variations of transmission line reactance, load susceptance & rotor inertia constant; states predominantly contributing to mode 3 are edp & eqp, to mode 1, ids and to mode 2, iqs & w. Mode 2 & mode 5 and mode 3 & 4 can be merged as 2 modes respectively.

❑ So, instead of 5 modes, 3 modes are sufficient enough to define the system stability.

❑ For higher values of x & b11, critical Eigen value locus moves away from imaginary axis towards the negative real axis direction. So the higher the values of x & b, the more stable the respective modes are.

❑ For higher values of h, critical Eigen value locus moves towards the imaginary axis. So the higher the values of h, the probability of the respective modes of becoming unstable increases.

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