Small Signal Stability Analysis of Large Scale Variable Speed Wind Turbine Integration

Major Project Report

Submitted in Partial Fulfillment of the Requirements for the

Degree of

Master of Technology
in
Electrical Engineering
(Electrical Power Systems)

By

Pinak Deb
15MEEE17

DEPARTMENT OF ELECTRICAL ENGINEERING
INSTITUTE OF TECHNOLOGY
NIRMA UNIVERSITY
AHMEDABAD-382481

December-2016

CERTIFICATE

This is to certify that the Major Project Report entitled "Small Signal Stability Analysis of Large Scale Variable Speed Wind Turbine Integration" submitted by Mr. Pinak Deb (15MEEE17) towards the partial fulfillment of the requirements for the award of degree in Master of Technology (Electrical Engineering) in the field of Electrical Power Systems of Nirma University is the record of work carried out by him under our supervision and guidance. The work submitted has in our opinion reached a level required for being accepted for examination. The results embodied in this major project work to the best of our knowledge have not been submitted to any other University or Institution for award of any degree or diploma.
Date : /05/2017

Prof. Shanker Godwal
Assistant Professor
Department of Electrical Engineering
Institute of Technology
Nirma University
Ahmedabad

Dr. P.N. Tekwani
Head of Department
Department of Electrical Engineering
Institute of Technology
Nirma University
Ahmedabad

Dr. Alka Mahajan
Director
Institute of Technology
Nirma University
Ahmedabad
.

Annexure VI

Undertaking for Originality of the Work

I, **Pinak Deb, Roll No. 15MEEE17**, give undertaking that the Major Project entitled **Small Signal Stability Analysis of Large Scale Variable Speed Wind Turbine Integration** submitted by me, towards the partial fulfillment of the requirements for the degree of Master of Technology in **Electrical Power Systems, Electrical Engineering** of Nirma University, Ahmedabad, is the original work carried out by me and I give assurance that no attempt of plagiarism has been made. I understand that in the event of any similarity found subsequently with any published work or any dissertation work elsewhere; it will result in severe disciplinary action.

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Date: ....

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....
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Acknowledgement

I would like to express my immense gratitude to my project guide Prof. Shanker Godwal, Department of Electrical Engineering, Nirma University, Ahmedabad for his valuable guidance and continual encouragement throughout my project work. His constant support and interest equipped me with a great understanding of different aspects.

A special thanks to Dr. P. N. Tekwani(Head of Department) and Dr. Santosh C. Vora(PG coordinator EPS), of Department of Electrical Engineering, Institute of Technology, Nirma University, Ahmedabad for providing such a wonderful platform equipped with the most futuristic resources where, I can carry out my major project work.

Most importantly deepest appreciation and thanks to Almighty and my family for their unending love, affection and personal sacrifices during the whole tenure of my study.

Abstract

Due to increase in the amount of pollution globally, modern power systems are incorporating renewable sources to generate electricity. Out of the several renewable sources, wind energy is gaining maximum height in terms of power generation in the present scenario. Out of the various wind turbine generators, the variable speed wind turbine generator or doubly fed induction generator is widely used since, the DFIGs are capable of offering higher efficiency in capturing the wind energy over a wide range of wind speeds, with better power quality. As the integration of wind energy is immensely increasing, it has become important to analyze the effect of wind generation on small signal stability. This paper thus, will thus discuss the small signal stability of large scale variable speed wind turbine with DFIG incorporation into modern power system. The small signal stability analysis is done following conventional eigen value or modal analysis method.

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Abbreviation and Nomenclature

AVR	Automatic Voltage Regulator
DFIG	Doubly Fed Induction Generator
GSC	Grid Side Converter
IEEE	Institute of Electrical and Electronic Engineers
PSS	Power System Stabilizer
RSC	Rotor Side Converter
SMIB	Single Machine Infinite Bus
WPP	wind Power Plants
WSCC	Western System Coordinating Council
WTG	Wind Turbine Generator
$\Delta\delta$	Synchronizing Torque Component
$\Delta\omega$	Damping Torque Component
P	Active Power
Q	Reactive power
T_D	Damping Torque Coefficient
T_s	Synchronizing Torque Component

Chapter 1

Introduction to Small Signal Stability of Power System

Small signal stability analysis of a power system at a given instant could be defined as the ability of how a power system can to maintain it's synchronism when perturbed to small disturbances. Such disturbances occur continuously to the given power system because of small perturbation or deviation of load and generation. The disturbances could be considered very small so that the system equation could be linearized for the purpose of system analysis.
Instability on the system could be of two types (i) steadily increasing rotor angle due to insufficient synchronizing torque, or (ii) increase in the amplitude of rotor angle because of insufficient damping torque.
The nature in which a system would respond to small disturbances depends upon various factors which are: the initial operating condition, the strength of the transmission system and the type of excitation control used for generators.
If a generator is connected radially to a large power system, in the absence of AVRs the instability basically happens due to lack of sufficient synchronizing torque. This in turn results in an instability because of a non-oscillatory mode.
When voltage regulators are acting continuously, the small disturbance stability problem basically happens because of lack of insufficient damping torque.
Instability is mainly because of oscillation of increasing amplitude.

1.1 Nature of Response Due to Small Disturbance

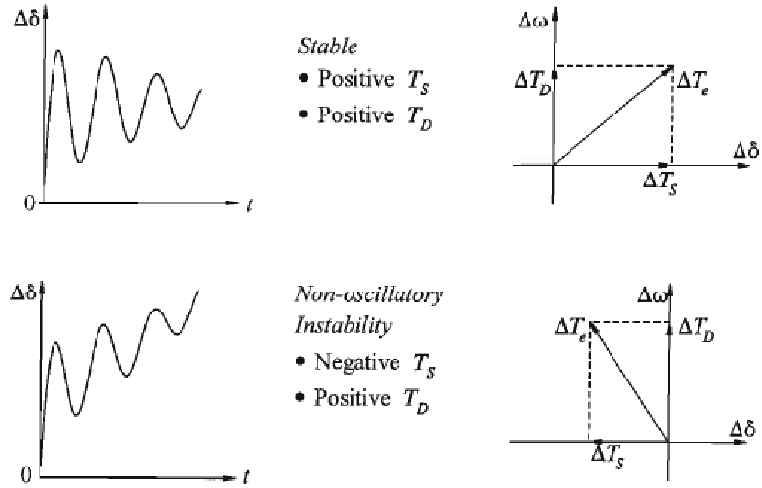

Figure 1.1: Nature of Small Disturbance Response Without AVR

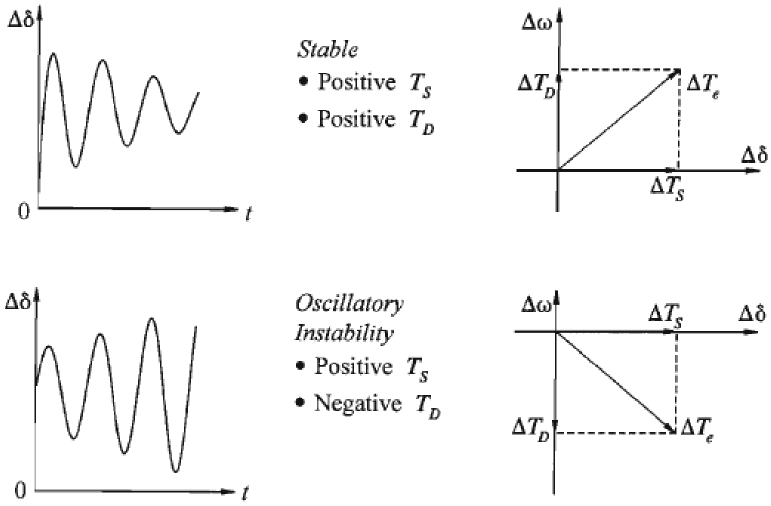

Figure 1.2: Nature of Small Disturbance Response With AVR

1.2 Modes of Electromechanical Oscillations

- **Intra Plant Mode of Oscillations:** This is a type of oscillation, in which the generators in a power plant participate towards oscillation. The frequencies of oscillation are high which is in the range of 1.5 to 3 HZ.
- **Local Mode of Oscillation:** Here, in this local mode, several generators with in an area would participate towards oscillation. The frequencies of oscillation are with in the range of 0.8 to 1.8 Hz.
- **Inter Area Modes of Oscillations:** In this mode of inter area oscillation, the generators over an extensive area would participate in the process of oscillation. The frequencies of oscillation areo in the range of 0.2 to 0.5Hz.
- **Control Modes:** Control modes of oscillations are basically associated with generating units and other controls./e.g Exciters which are poorly tuned, HVDC converters, static var compensators and speed governors are responsible for such instabilities.
- **Torsional Modes of Oscillations:** Torsional modes of oscillations are basically associated with rotational components of turbine generator shaft system .

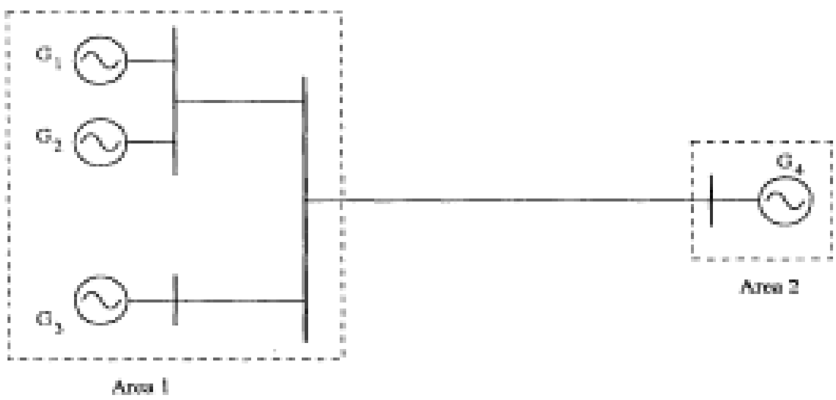

Figure 1.3: A Power System

1.3 Introduction to Wind Energy

Wind energy is a renewable source of energy for electricity production.
Since the conventional and or the non renewable sources of energy is harming the environment adversely, the renewable sources of energy are gaining importance rapidly. Wind energy is the most widely is one of the most largely available and exploitable sources of energy. Wind blows because of change in the atmospheric pressure and is also a by-product of solar energy. Hence, it is considered as the most viable source of electrical power and is economically competitive with the conventional or the non renewable sources.
Wind turbines generates electricity by using the wind power as a source drive an electrical generator.
As wind flows over the blades of a wind turbine, a lift force is generated thereby, exerting a turning force. The rotating blades will turn a low speed shaft which is installed inside the nacelle. The nacelle houses the low speed shaft, the gear box, the high speed shaft and the generator. The speed of the low speed shaft passes through the gear box. the gear box connects the low speed shaft with the high speed shaft. the gear box boosts the rotational speed of the high speed shaft. This rapidly spinning shaft will drive the generator to produce electric power.which goes into a gearbox.
The output power from the generator goes to a transformer. The transformer converts the electricity from the generator to an appropriate voltage for the power collection system.
A wind turbine will extract kinetic energy from the swept area of the blades. A wind turbine converts the kinetic energy present in the wind into a form of mechanical energy. Since, the energy possessed by the wind is in the form of kinetic energy, its magnitude depends on the density of air and the velocity of wind. The power output produced by a wind turbine is given by:

$$P = 0.5 * C_p * A * \rho * V^3 \tag{1.1}$$

Hence, from the output power equation of wind turbine we may conclude that output power is proportional to cube of velocity of wind, air density and the swept area of the blade.
In 1920, a German scientist named Albert Betz, pioneered wind power technology, studied the best utilization of wind energy in wind mills and established a theoretical limit for the power extracted by a wind turbine. Basically, it said that at the most 59% of the kinetic energy of the wind can be converted into mechanical energy. This is known as Betzs limit. Also at every speed of the wind, there is an optimum speed of the turbine at which the power extracted from the wind will be maximized.

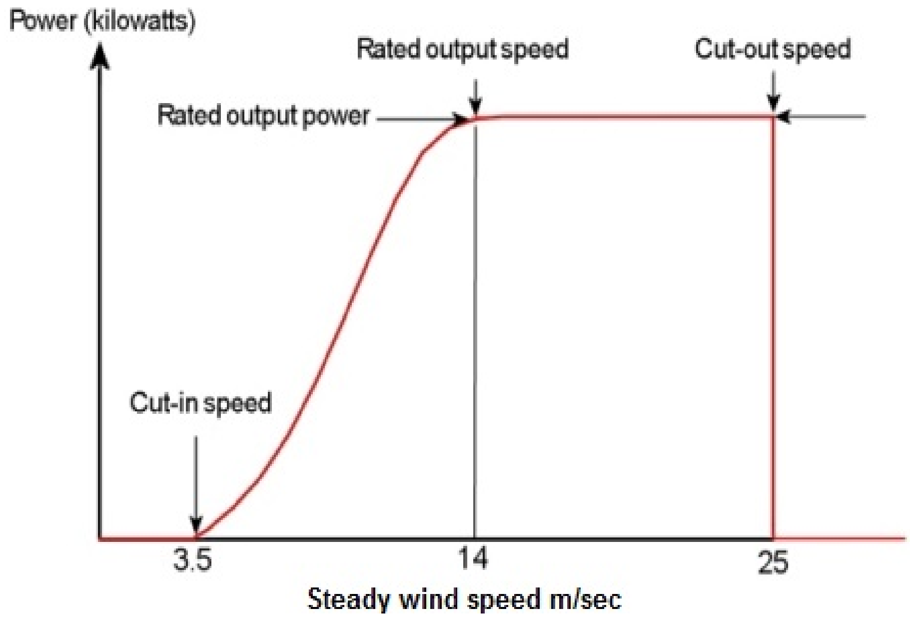

Figure 1.4: Typical Wind Turbine Power Output With Steady Wind Speed

- The power coefficient is defined as the amount of energy extracted from the wind by the wind turbine.
- The power coefficient would vary according to design of the rotor and the relative speed of the rotor and the wind.
- From the power curve given in the above diagram, at the wind speed below cut in speed not much significant amount power is produced.
- As the output power increases rapidly with increase in the wind speed, it reaches its rated value which is then limited by the turbine control mechanism.
- This part of the system maintains a cubic relationship between wind speed and power output which can be modified by varying the power coefficient.
- At cut out wind speed, the rotor is allowed to remain idle at low speed to ensure safety measures.

1.4 Classification of Wind Turbine

Wind turbines are classified into two general types: Horizontal axis wind turbines and Vertical axis turbines.

- **Horizontal Axis Wind Turbine**
  A horizontal axis wind turbine has blades which rotates on an axis which is parallel to the ground. In addition to being parallel to the ground, the axis of rotation of the blade is also parallel to the wind flow. It is basically classified into two types; upwind mode where, the rotor faces towards the direction of the wind and downwind mode where, the rotor of the machine faces on lee side of the tower.

- **Vertical Axis Wind Turbine**
  In a vertical axis wind turbine blades rotates on an axis which is perpendicular to the ground. Vertical axis wind turbines are less efficient as compared to horizontal axis wind turbines. The basic vertical axis designs are generally classified as the Darrieus, which consists of curved blades, the Giromill, which has straight blades and the Savonius, which uses scoops to catch the wind. The designs of the vertical axis wind turbines are not as efficient at collecting energy from the wind as are the horizontal axis wind turbine.

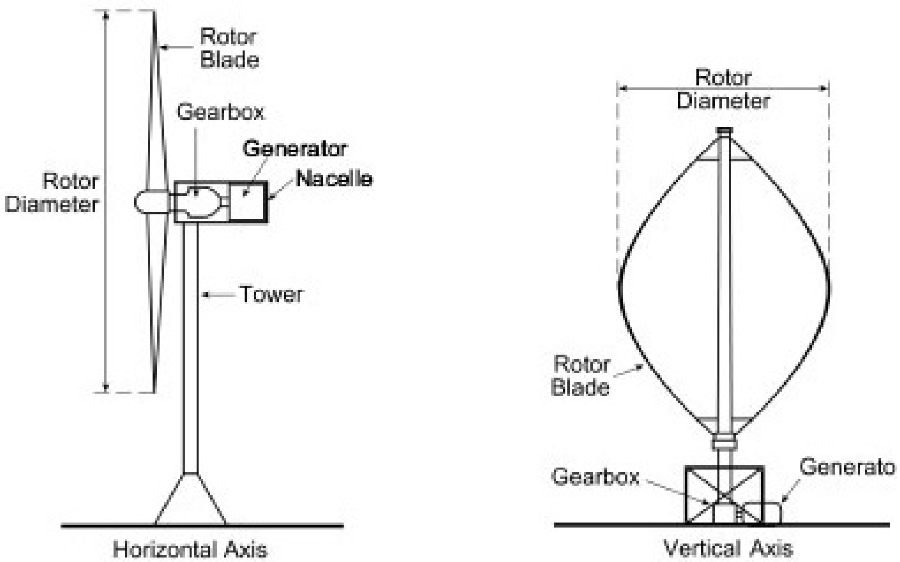

Figure 1.5: Horizontal Axis and Vertical Axis Wind Turbine

1.5 Types of Wind Turbine Technology

1. **Type-1 Wind Turbine Generator**
   Type-1 wind turbines consists of squirrel cage induction generator which is directly connected to a step up transformer.
   Speed of the turbine is fixed to the electrical grid frequency and will generate real power the shaft of the turbine would rotate faster than the electrical grid frequency hence, it will create a negative slip.
   Major disadvantage of the induction machine is the large amount of reactive power which it absorbs for its excitation field and the large amounts of currents which it draws when started across the line.
   In such a case a soft starter and capacitor banks may be used to reduce these effects.

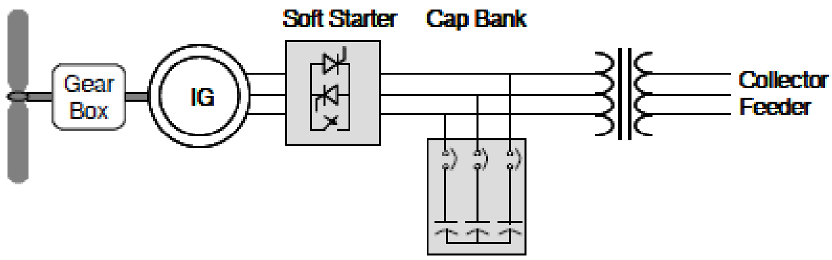

Figure 1.6: Type-1 WTG

Type-2 Wind Turbine Generator
In type-2 wind turbines, wound rotor induction generators are directly connected to the wind turbine generator step up transformer it also consists of a variable resistor in the rotor circuit.
The variable resistors are connected external to the rotor circuit so as to control the rotor currents in order to keep power constant even during heavy condition of wind.

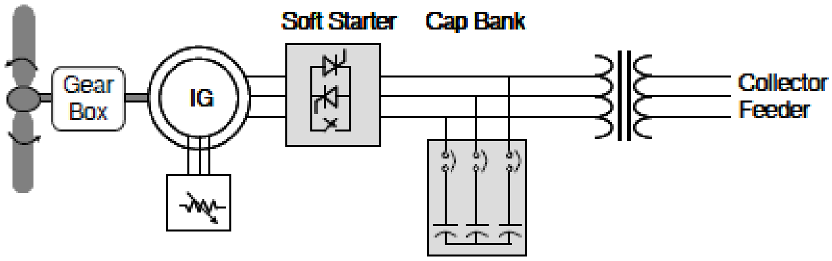

Figure 1.7: Type-2 WTG

Type-3 Wind Turbine Generator
Type-3 wind turbine generator or a doubly fed induction generator is a wind turbine generator in which the stator terminal is directly connected to the grid and the rotor circuit is connected to a converter. A gear box is generally connected between the generator and the rotor due to the difference between rotor and generator speeds.The converters are variable frequency and back to back ac to dc to ac voltage source type converters.These basically consists of IGBT converters which are rotor side converter and a grid side converter. The converters will decouple the electrical grid frequency and the mechanical frequency of the rotor thereby providing variable speed operation. The rotor side converters helps in controlling the active and reactive powers and harmonics of the generator whereas, the grid side converters controls the power factor.

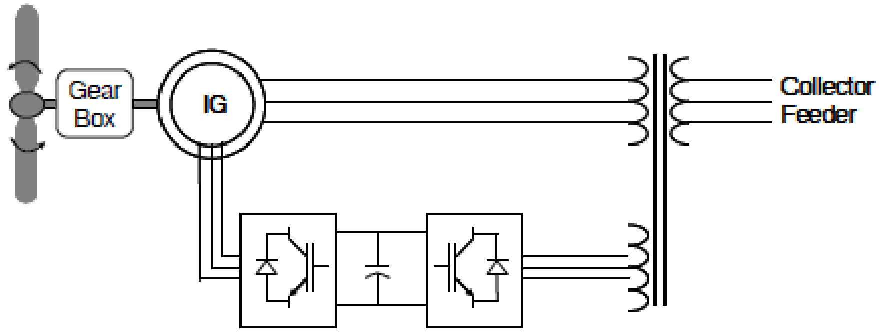

Figure 1.8: Type-3 WTG

Type-4 Wind Turbine Generator
A type-4 wind turbine generator is the one in which the roting machine's output is passed to the grid through a full scale back to back frequency converter thereby providing a high range of flexibility in its design and operation. The gear box is eliminated so that the machine rotates at slower turbine speed is possible thereby providing an electrical frequency which is below the grid frequency.The rotating machine of of this type of wind turbine generator consists of a wound rotor synchronous machine.

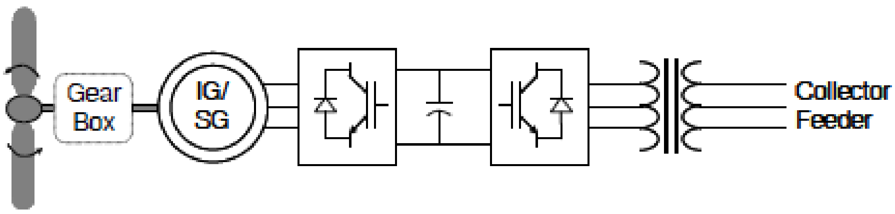

Figure 1.9: Type-4 WTG

1.5.1 Objective

Due to the lower inertia of wind turbine the nature of oscillation will be changed.Because of this reason, the nature of frequency of oscillation will be changed.So, the objective of the project is to calculate the oscillation frequencies.This will give the idea that to what extent oscillation frequencies are different than the conventional grid.The outcome of this project will be the base for the studies like PSS tuning of synchronous generator,subsynchronous resonance etc.

1.5.2 Methodology

1. Implementation of WSCC 9 bus standard system.

2. Load flow analysis of WSCC 9 bus system.

3. Eigen value and modal analysis of WSCC 9 bus system in normal condition followed by eigen value and modal analysis of WSCC 9 bus system with a change of 50MW load in bus number 5.

4. Modelling of doubly fed induction generator i.e a typeIII wind turbine generator.

5. Load flow analysis of WSCC 9 bus sytem with DFIG incorporated at bus number 2 i.e replace syncghronous generator with a DFIG at bus number 5.

6. Eigen value analysis of DFIG system in normal condition followed by eigen value and modal analysis of the DFIG system with a change in 50MW load in bus number 5.

7. Comparison and analysis of all the different condition in context to the eigen value and modal analysis for system stability .

Chapter 2

Literature Survey

[1] **Xian Li, Zhiyuan Zeng, Jianhong Zhou, Yongchuan Zhang, "Small Signal Stability Analysis of Large Scale Variable Speed Wind Turbine Integration,"Electrical Machines and Systems, 2008 ICEMS 2008 International Conference**
The author here shows the performance of small signal stability analysis of large scale integration of DFIG machine into the grid. Modal analysis has been performed that is usually used in small signal analysis and is also considered as a reliable tool to analyse the power system.
In this method of stability analysis i.e, in nodal method eigen value analysis has been done which takes into consideration the right and the left eigen vectors of a Jacobian matrix which is obtained from power flow equations.
The author has also proposed that FACTS devices can also be used to minimize the oscillations due to instability.

[2]**Chongtao Li, Zhengchun Du, "A Novel Method for Computing Small Signal Strability Boundaries of Large-Scale Power System", IEEE member, September 2012**
The author here mentions a novel method to analyse the changing values of a controller which allows the eigen values to cross boundaries of small signal stability.
In this process, the author explains how to determine the crossing point of eigen value locus and the boundary without calculating the eigen values or eigen values of the state matrix.

[3] **S.Muller, M.Deicke, De Doncker, "Doubly Fed Induction Generator System for Wind Turbines", IEEE Industry Applications Magazine MaY-June 2002**
This paper discusses the various advantages of adjustable speed generators such as its cost effectiveness, reduced mechanical stress, dynamic compensation for torque and power and power pulsation caused by back pressure of tower, improved power quality, improved system efficiency, reduced acoustic noise. The author here in this

paper mentions the various cons of direct in-line adjustable speed generators and hence, provides an alternative which is an adjustable speed generator .

[4]**Prabha Kundur, "Power System Stability and Control", Mc Graw Hill Education, 2014.**

Introduction to power system stability problem including basic concepts and definitions, classification of stability, historical review of stability problems.

Small signal stability, fundamental concepts of stability of dynamic systems, eigen properties of state matrix, small signal stability analysis of single-machine infinite bus system.

[5] **R. Ramanujam, "Power System Dynamics Analysis and Simulation", PHI Learning Private Limited, 2009.**

Detailed learning about power system stability- elementary analysis, small signal stability analysis of power system.

[6] **Joshua Earnest, "Wind Power Technology", PHI Learning Private Limited, 2015.**

This book provides a detailed information about wind resource, wind power plant, various parts and structures of a wind turbine, wind energy conversion, wind turbine aerodynamics, constant speed wind power plants and variable speed wind power plants

[7] **K.R. Padiyar, "Power System Dynamis: Stability and Control", Wiley, 1999.**

This book gives a detailed insight on modern power system dynamics, transient stability problems, stability by reviewing on classical machine modelling, small signal stability of power system including various types of electromechanical oscillations.

[8] **Binal Mehta,Vivek Pandya, Pragnesh Bhatt, "Small signal stability analysis of power systems with DFIG based wind power penetration", Department of Electrical Engineering, C.S. Patel Institute of Technology, CHARUSAT, Changa, Gujarat, India Department of Electrical Engineering, School of Technology, PDPU, Gandhinagar, Gujarat, India, January 2014**

The author here in this paper makes a detailed analysis on the effect of wind power integration by DFIG on power system oscillation, by taking into consideration a two area inter connected power system.

[9] **Durga Gautam, Vijay Mittal, "Impact of Increased Penetration of DFIG-Based Wind Turbine Generators on Transient and Small Signal Stability of Power Systems",IEEE member, May 2009**

The author here in this paper makes a detailed analysis on the effect of wind power integration by DFIG on power system oscillation, by taking into consideration a two area inter connected power system.

Chapter 3

Case Study: To Analyze Effect of DFIG Integration On System Inertia

3.1 Load Flow of WSCC 9 Bus System (60Hz)

- **Case1:**
  Figure 3.2 shows the load flow of a WSCC 9 bus system with 60 Hz of frequency with out any change in load. Three machines namely Machine-2 and Machine-3 (Steam Turbine Generator) and Machine-1(Hydro Turbine Generator) has been connected to the system at bus- 2, 3 and 1 respectively.

  Machine1 is rated as:247.5MVA
  Machine 2 is rated as:192MVA
  Machine 3 is rated as:128MVA
  Figure 3.3 shows the load angles of Machine-1, Machine-2 and Machine-3 under normal condition that is without out any significant change in load in the current system under analysis.
  Fig.3.1 shows the instantaneous bus voltages at all the buses remain in synchronism after the load flow has been performed.

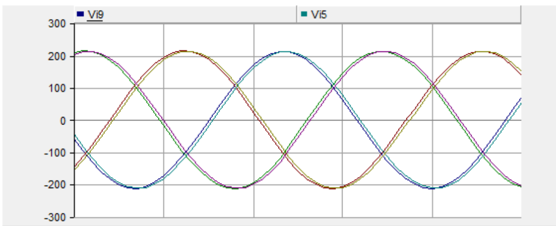

Figure 3.1: Fig. Showing Instantaneous Bus Voltage

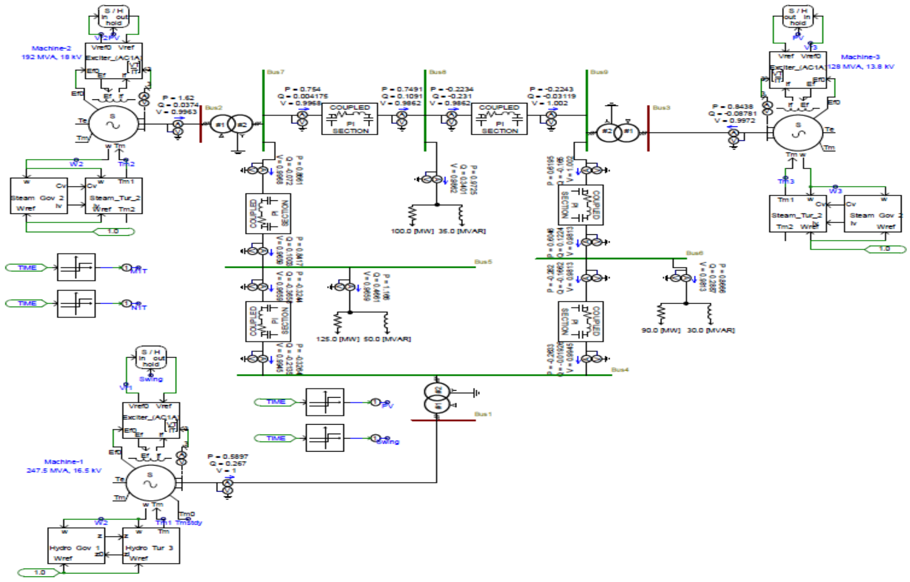

Figure 3.2: Load Flow Analysis of WSCC 9 Bus System with 60 Hz Frequency

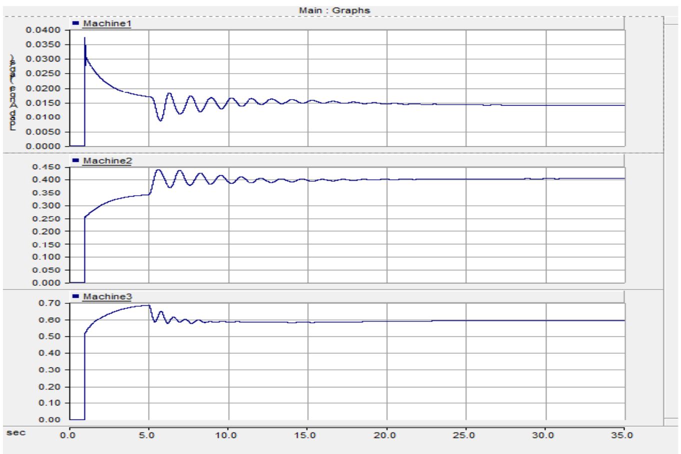

Figure 3.3: Waveforms Showing Variation of Load Angles

3.1.1 Load Flow With 25 MW Change in Load

- **Case2**:
  Fig.3.4 shows the load flow of WSCC 9 bus system with 25 MW decrease in load in bus-5 .
  Fig.3.5 shows the variation in load angles of the three machines as a result of reduction of 25 MW load at bus-5.
  Fig.3.6 shows the synchronism of the bus voltages

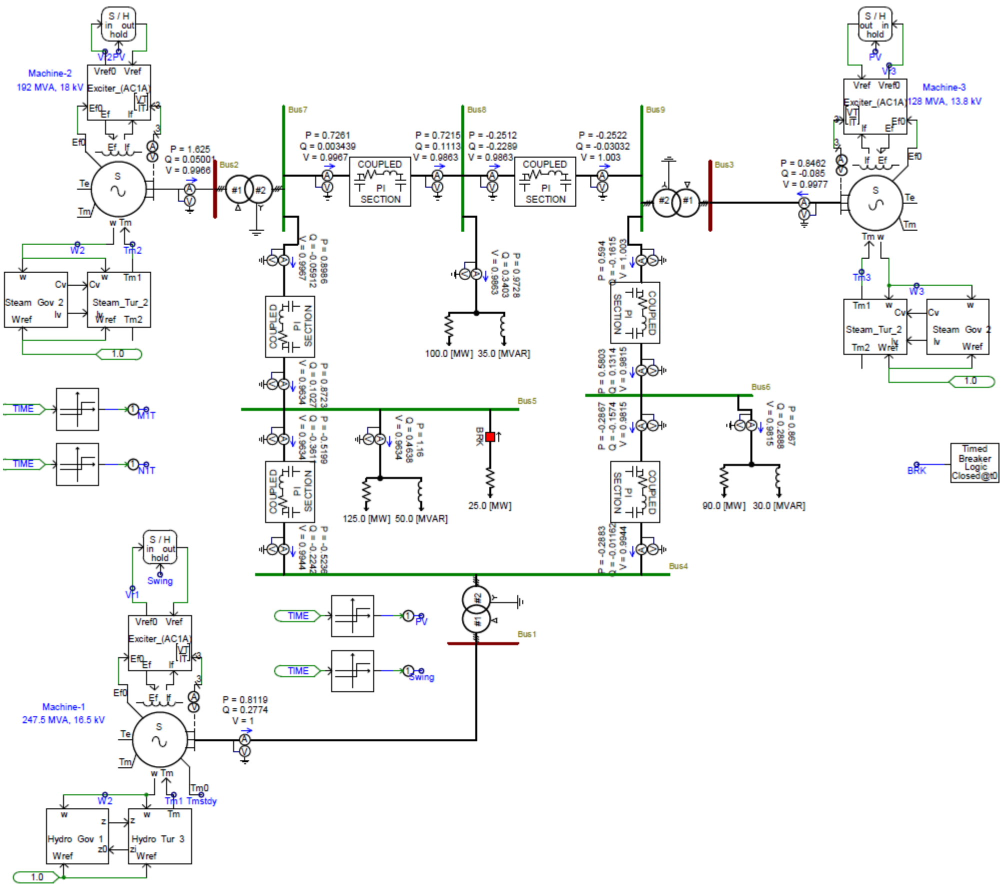

Figure 3.4: Load Flow With 25 MW Decrease in Load at Bus-5

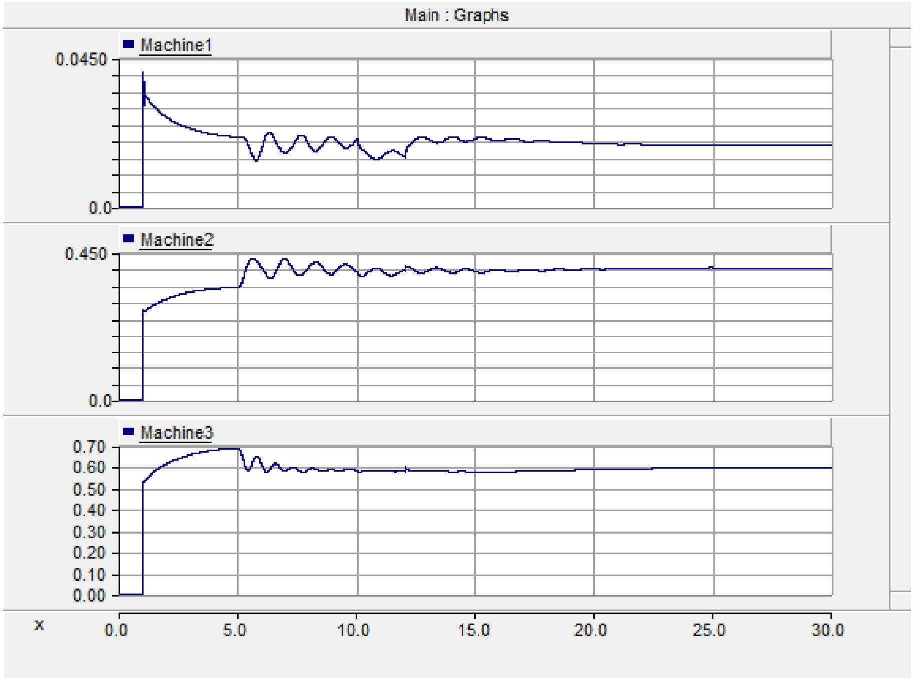

Figure 3.5: Variation in Load Angles With 25 MW Decrease at Bus-5

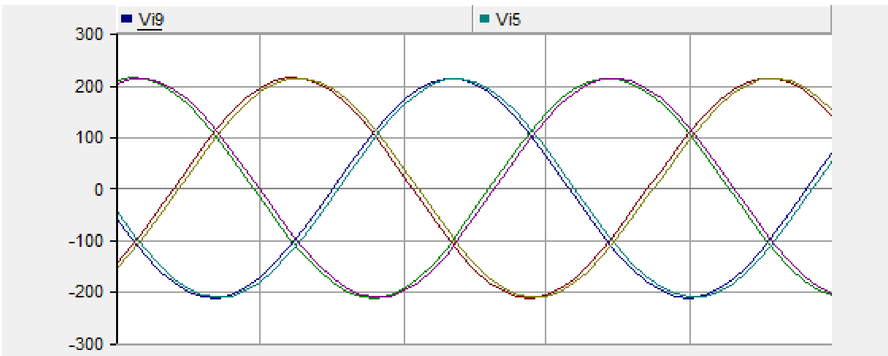

Figure 3.6: Fig. Showing Instantaneos Bus Voltages

3.2 Load Flow With Type-3 WTG Integration

- **Case1**

Fig.3.19 shows a WSCC 9 bus system in which a DFIG or a type-3 wind turbine generator has been integrated at bus-2. The results so obtained would be described in the following section.
Fig.3.20 and fig.3.21 respectively shows the variation or change in load angles of Machine-1 and Machine3 and the corresponding power change i.e. active and reactive power of bus-1 and bus-2 respectively due to the integration of a DFIG wind turbine into the system under analysis

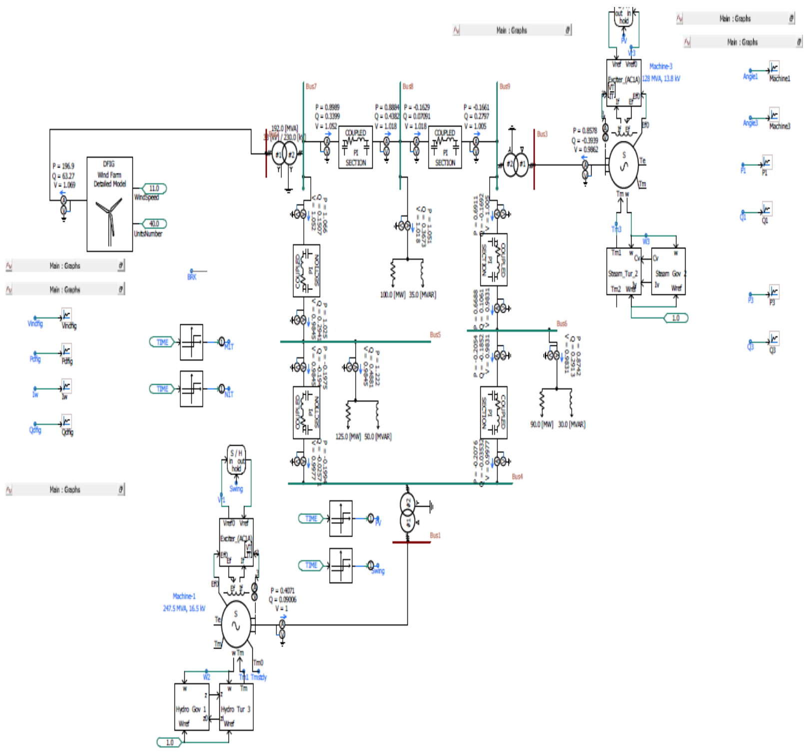

Figure 3.7: WSCC 9 Bus With Type-3 WTG Integration

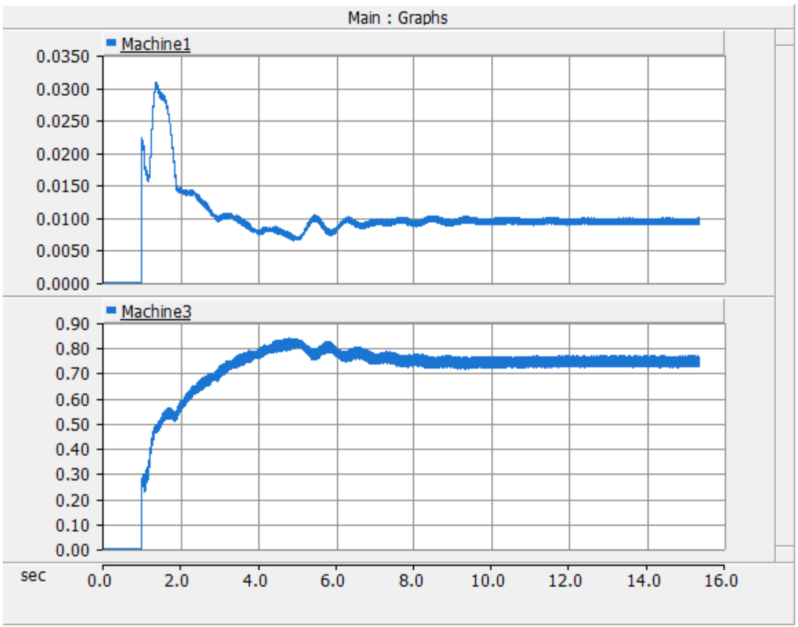

Figure 3.8: Variation of Load Angle in Machine-1 and Machine-3

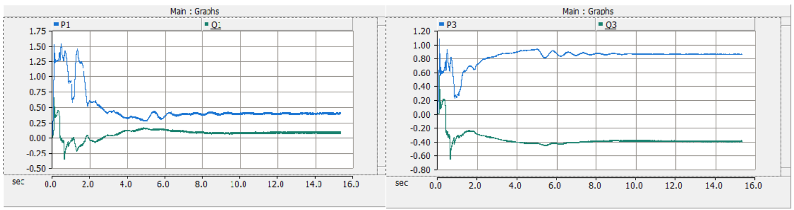

Figure 3.9: Variation of P1,Q1,P3,Q3

3.2.1 Load Flow With Type-3 WTG Integration and Change in Load

- **Case2**

Fig.3.22 shows a WSCC 9 bus system in which a DFIG or a type-3 wind turbine generator has been integrated at bus-2. The results so obtained would be described in the following section,
Fig.3.23 and fig.3.24 respectively shows the variation or change in load angles of Machine-1 and Machine-3 and the corresponding power change i.e. active and reactive power of bus-1 and bus-2 respectively due to the combined effects of integration of DFIG wind turbine and a decrease in load of 25 MW into the system under analysis under analysis

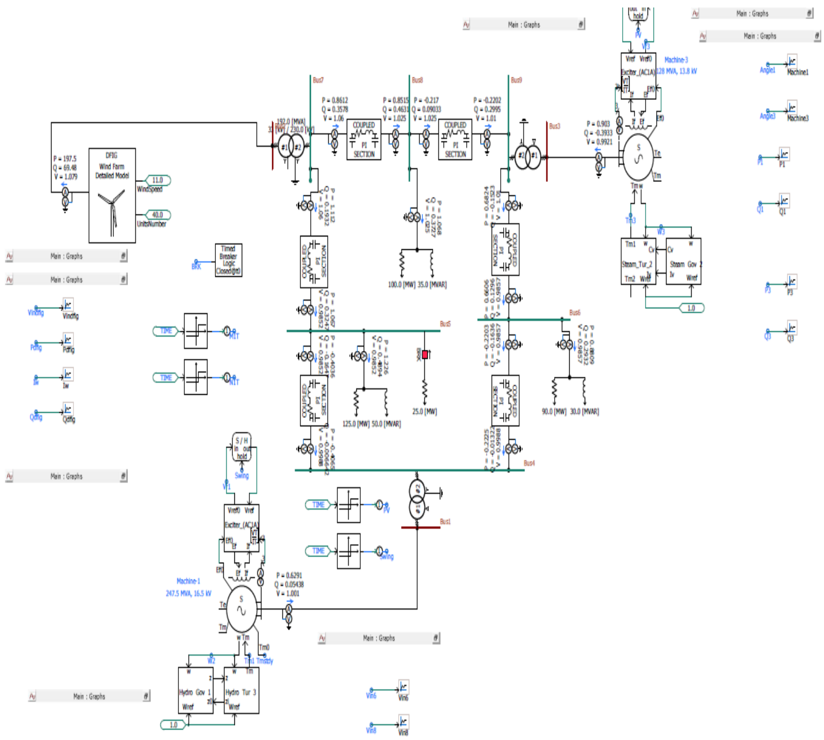

Figure 3.10: WSCC 9 Bus With Type-3 WTG Integration (With Change in Load)

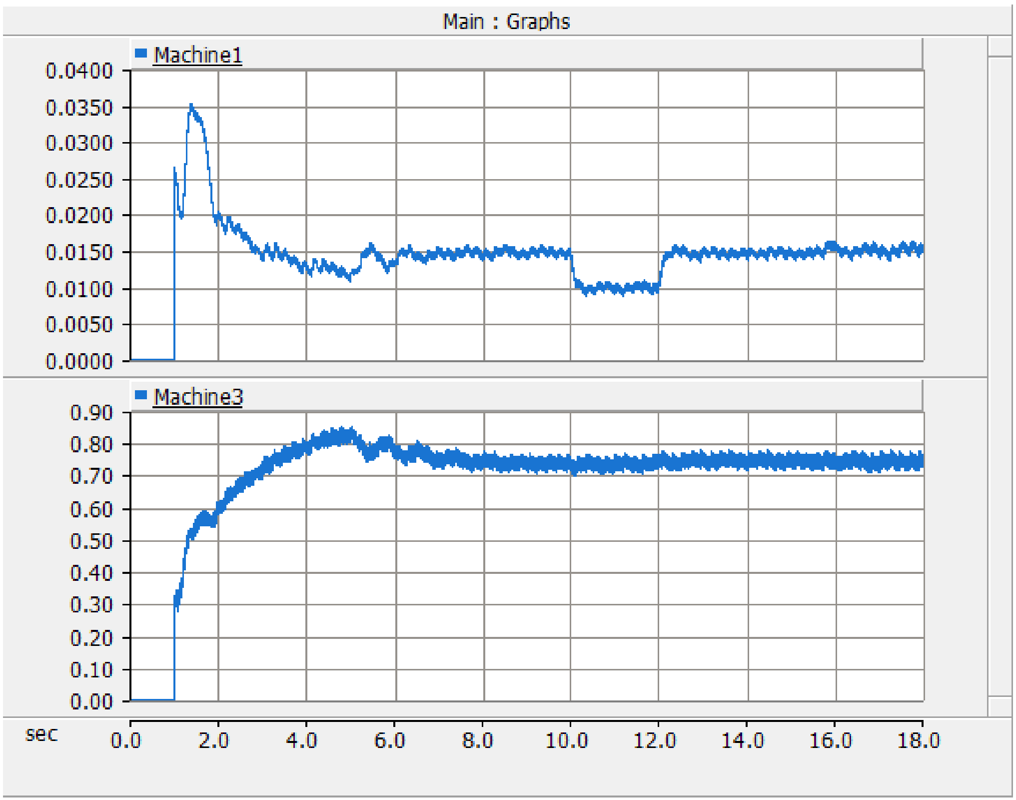

Figure 3.11: Variation of Load Angle in Machine-1 and Machine-3

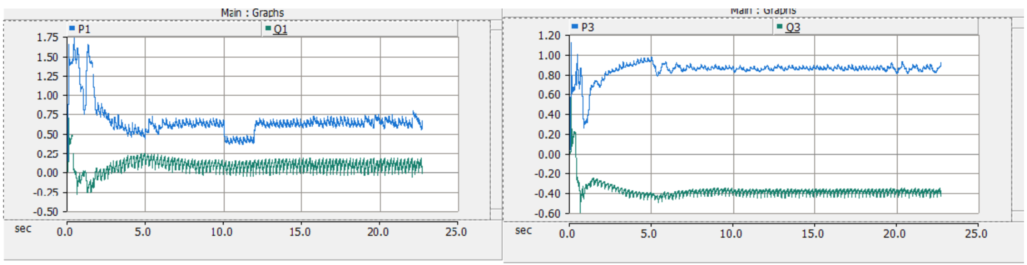

Figure 3.12: Variation of P1,Q1,P3,Q3

3.3 Analysis And Result

- For the purpose of analysis, load flow of a normal WSCC 9 bus system was performed.

- The WSCC 9 bus system was then subsequently integrated with Type-3 WTG and a load flow was again performed to analyze the influence of the wind turbine generators into the system.

- The objective of the analysis was to check that, upon inclusion of DFIG to the power system, how the variable speed wind generator affects the inertia of the system.

- A reduction of 25 MW load was then introduced to the load connected in bus-5 whose initial load was 125 MW. Now, with this condition the systems were again analyzed.

- The load was thrown off for a very short period of 2 seconds.

- Under all the situations, the variations in the load angles of the machines were observed, along with the changes in active and reactive power generation and absorbed.

The results are thus discussed:

1. In case of a normal WSCC 9 bus with conventional generators, with change in load, the graph shows that, the settling time of load angle is lesser compared to the system having WTG integration.

2. This result shows that the lower inertia of wind turbine is influencing the settling time of the load angle.

3. The prolonged oscillations after WTG integration is a base for the analysis of small signal stability.

4. This results are basically happens due to the low inertia of wind turbine.

5. Fig.3.20 shows that the load angle has oscillations even under normal condition with out any change in loading condition .

Chapter 4

Case Study for Eigen Value Analysis and Modal Analysis

4.1 For WSCC 9 Bus System.

- **Case1:**

Sr. No.	**Eigen Value Bus1**	**Eigen Value Bus2**	**Eigen Value Bus3**
1	-0.0235 + j0.0000	-0.4100 - j0.7272	-0.4201 - j0.5578
2	-0.4303 - j0.8991	-0.4100 + j0.7272	-0.4201 + j0.5578
3	-0.4303 + j0.8991	-3.7167 + j0.0000	-3.2241 + j0.0000
4	-1.9210 + j0.0000	-5.4354 + j0.0000	-6.6766 + j0.0000
5	-3.2258 + j0.0000	-5.1631 + j7.8581	-5.1707 + j7.8753
6	-0.0501 + j4.8884	-5.1631 - j7.8581	-5.1707 - j7.8753
7	-0.0501 - j4.8884	-0.3856 - j10.3814	-0.5284 + j13.3525
8	-5.1676 - j7.8166	-0.3856 + j10.3814	-0.5284 - j13.3525
9	-5.1676 + j7.8166	-14.9205 + j0.0000	-14.0157 + j0.0000
10	-12.1390 + j0.0000	-31.8433 + j0.0000	-33.0840 + j0.0000
11	-22.4810 + j0.0000	-37.0327 + j0.0000	-37.1571 + j0.0000
12	-23.7256 + j0.0000		
13	-35.7701 + j0.0000		

Table 4.1: Eigen Value Analysis

Sr. No.	Frequency(Hz)	Damping%	Lambda
1	0.344	8.819	-0.1913
2	0.474	4.119	-0.1227
3	0.996	59.309	-4.6097
4	0.9	15.909	-0.9117
5	0.662	3.768	-0.1569

Table 4.2: Modal Analysisis

Row Name	Machine Angle	Machine Speed w	Machine Eqp	Machine PsiDp	Machine PsiQpp	Machine Edp	Exciter EField	Exciter VR	Exciter VF	Governor Filter Output	Governor Desired Gate	Governor Gate	Governor Turbine Flow
Machine Angle	0	376.9911	0	0	0	0	0	0	0	0	0	0	0
Machine Speed w	-0.0719	-0.0463	-0.0123	-0.0256	0.0571	0.01	0	0	0	0	0	-0.1789	0.3058
Machine Eqp	0.0006	-0.011	-0.3235	0.2015	-0.0025	-0.0004	0.1116	0	0	0	0	0	0
Machine PsiDp	0.204	-3.651	32.2163	-35.6567	-0.829	-0.1457	0	0	0	0	0	0	0
Machine PsiQpp	4.3421	1.1632	0.4124	0.8578	-23.8134	19.3298	0	0	0	0	0	0	0
Machine Edp	0	0	0	0	0	-3.2258	0	0	0	0	0	0	0
Exciter EField	0	0	0	0	0	0	-3.1847	3.1847	0	0	0	0	0
Exciter VR	-1.6045	-91.0942	-28.1377	-58.5264	-1.3785	-0.2423	-18	-5	-100	0	0	0	0
Exciter VF	0	0	0	0	0	0	-0.5143	0	-2.8571	0	0	0	0
Governor Filter Output	0	-20	0	0	0	0	0	0	0	-22.6667	-0.8	0	0
Governor Desired Gate	0	0	0	0	0	0	0	0	0	0.6667	0	0	0
Governor Gate	0	0	0	0	0	0	0	0	0	6.6667	2	-2	0
Governor Turbine Flow	0	0	0	0	0	0	0	0	0	0	0	11.8078	-11.8078

Figure 4.1: A matrix for Machine 1

Row Name	Machine Angle	Machine Speed w	Machine Eqp	Machine PsiDp	Machine PsiQpp	Machine Edp	Exciter EField	Exciter VR	Exciter VF	Governor Governor Output	Governor Turbine Bowl
Machine Angle	0	376.9911	0	0	0	0	0	0	0	0	0
Machine Speed w	-0.2425	-0.1667	-0.1394	-0.1384	0.043	0.0121	0	0	0	0	0.1953
Machine Eqp	-0.1857	-0.1731	-1.3463	0.9765	-0.0236	-0.0066	0.1667	0	0	0	0
Machine PsiDp	-5.7043	-5.318	30.2023	-36.4435	-0.726	-0.2037	0	0	0	0	0
Machine PsiQpp	3.7841	-5.27	0.6407	0.6364	-26.6942	18.1214	0	0	0	0	0
Machine Edp	0.3779	-0.5262	0.064	0.0635	6.4481	-9.1733	0	0	0	0	0
Exciter EField	0	0	0	0	0	0	-3.1847	3.1847	0	0	0
Exciter VR	5.9583	-74.526	-23.7484	-23.5901	-42.3027	-11.8717	-18	-5	-100	0	0
Exciter VF	0	0	0	0	0	0	-0.5143	0	-2.8571	0	0
Governor Governor Output	0	-250	0	0	0	0	0	0	0	-10	0
Governor Turbine Bowl	0	0	0	0	0	0	0	0	0	10	-10

Figure 4.2: A matrix for Machine 2

Row Name	Machine Angle	Machine Speed w	Machine Eqp	Machine PsiDp	Machine PsiQpp	Machine Edp	Exciter EField	Exciter VR	Exciter VF	Governor Governor Output	Governor Turbine Bowl
Machine Angle	0	376.9911	0	0	0	0	0	0	0	0	0
Machine Speed w	-0.4576	-0.1905	-0.2169	-0.2263	0.157	0.0471	0	0	0	0	0.1661
Machine Eqp	-0.2104	-0.2053	-1.8919	1.4721	-0.0208	-0.0062	0.1698	0	0	0	0
Machine PsiDp	-4.5735	-4.4642	30.6734	-36.1085	-0.4518	-0.1355	0	0	0	0	0
Machine PsiQpp	4.2237	-4.2035	0.3657	0.3816	-25.3198	18.4041	0	0	0	0	0
Machine Edp	0.6297	-0.6267	0.0545	0.0569	9.1458	-11.8434	0	0	0	0	0
Exciter EField	0	0	0	0	0	0	-3.1847	3.1847	0	0	0
Exciter VR	3.1293	-61.1333	-20.6327	-21.5268	-33.1158	-9.9348	-18	-5	-100	0	0
Exciter VF	0	0	0	0	0	0	-0.5143	0	-2.8571	0	0
Governor Governor Output	0	-250	0	0	0	0	0	0	0	-10	0
Governor Turbine Bowl	0	0	0	0	0	0	0	0	0	10	-10

Figure 4.3: A matrix for Machine 3

4.2 For WSCC 9 bus system With 50 MW Change at Bus-5

- **Case2:**

Sr. No.	Eigen Value Bus1	Eigen Value Bus2	Eigen Value Bus3
1	-0.0235 + j0.0000	-0.4100 - j0.7272	-0.4201 - j0.5578
2	-0.4303 - j0.8991	-0.4100 + j0.7272	-0.4201 + j0.5578
3	-0.4303 + j0.8991	-3.7167 + j0.0000	-3.2241 + j0.0000
4	-1.9210 + j0.0000	-5.4354 + j0.0000	-6.6766 + j0.0000
5	-3.2258 + j0.0000	-5.1631 + j7.8581	-5.1707 + j7.8753
6	-0.0501 + j4.8884	-5.1631 - j7.8581	-5.1707 - j7.8753
7	-0.0501 - j4.8884	-0.3856 - j10.3814	-0.5284 + j13.3525
8	-5.1676 - j7.8166	-0.3856 + j10.3814	-0.5284 - j13.3525
9	-5.1676 + j7.8166	-14.9205 + j0.0000	-14.0157 + j0.0000
10	-12.1390 + j0.0000	-31.8433 + j0.0000	-33.0840 + j0.0000
11	-22.4810 + j0.0000	-37.0327 + j0.0000	-37.1571 + j0.0000
12	-23.7256 + j0.0000		
13	-35.7701 + j0.0000		

Table 4.3: Eigen Value Analysis

Sr. No.	Frequency(Hz)	Damping(%)	Lambda
1	1	20.798	-1.336
2	0.71	26.515	-1.2265
3	0.096	-4.6	0.0277
4	0.214	43.641	-0.6518
5	0.433	24.849	-0.6973

Table 4.4: Modal Analysis

Row Name	Machine Angle	Machine Speed w	Machine Eqp	Machine PsiDp	Machine PsiQpp	Machine Edp	Exciter EField	Exciter VR	Exciter VF	Governor Filter Output	Governor Desired Gate	Governor Gate	Governor Turbine Flow
Machine Angle	0	376.9911	0	0	0	0	0	0	0	0	0	0	0
Machine Speed w	-0.0719	-0.0463	-0.0123	-0.0256	0.0571	0.01	0	0	0	0	0	-0.1789	0.3058
Machine Eqp	0.0006	-0.011	-0.3235	0.2015	-0.0025	-0.0004	0.1116	0	0	0	0	0	0
Machine PsiDp	0.204	-3.651	32.2163	-35.6567	-0.829	-0.1457	0	0	0	0	0	0	0
Machine PsiQpp	4.3421	1.1632	0.4124	0.8578	-23.8134	19.3298	0	0	0	0	0	0	0
Machine Edp	0	0	0	0	0	-3.2258	0	0	0	0	0	0	0
Exciter EField	0	0	0	0	0	0	-3.1847	3.1847	0	0	0	0	0
Exciter VR	-1.6045	-91.0942	-28.1377	-58.5264	-1.3785	-0.2423	-18	-5	-100	0	0	0	0
Exciter VF	0	0	0	0	0	0	-0.5143	0	-2.8571	0	0	0	0
Governor Filter Output	0	-20	0	0	0	0	0	0	0	-22.6667	-0.8	0	0
Governor Desired Gate	0	0	0	0	0	0	0	0	0	0.6667	0	0	0
Governor Gate	0	0	0	0	0	0	0	0	0	6.6667	2	-2	0
Governor Turbine Flow	0	0	0	0	0	0	0	0	0	0	0	11.8078	-11.8078

Figure 4.4: A matrix for Machine 1

Row Name	Machine Angle	Machine Speed w	Machine Eqp	Machine PsiDp	Machine PsiQpp	Machine Edp	Exciter EField	Exciter VR	Exciter VF	Governor Governor Output	Governor Turbine Bowl
Machine Angle	0	376.9911	0	0	0	0	0	0	0	0	0
Machine Speed w	-0.4576	-0.1905	-0.2169	-0.2263	0.157	0.0471	0	0	0	0	0.1661
Machine Eqp	-0.2104	-0.2053	-1.8919	1.4721	-0.0208	-0.0062	0.1698	0	0	0	0
Machine PsiDp	-4.5735	-4.4642	30.6734	-36.1085	-0.4518	-0.1355	0	0	0	0	0
Machine PsiQpp	4.2237	-4.2035	0.3657	0.3816	-25.3198	18.4041	0	0	0	0	0
Machine Edp	0.6297	-0.6267	0.0545	0.0569	9.1458	-11.8434	0	0	0	0	0
Exciter EField	0	0	0	0	0	0	-3.1847	3.1847	0	0	0
Exciter VR	3.1293	-61.1333	-20.6327	-21.5268	-33.1158	-9.9348	-18	-5	-100	0	0
Exciter VF	0	0	0	0	0	0	-0.5143	0	-2.8571	0	0
Governor Governor Output	0	-250	0	0	0	0	0	0	0	-10	0
Governor Turbine Bowl	0	0	0	0	0	0	0	0	0	10	-10

Figure 4.5: A matrix for Machine 2

Row Name	Machine Angle	Machine Speed w	Machine Eqp	Machine PsiDp	Machine PsiQpp	Machine Edp	Exciter EField	Exciter VR	Exciter VF	Governor Governor Output	Governor Turbine Bowl
Machine Angle	0	376.9911	0	0	0	0	0	0	0	0	0
Machine Speed w	-0.2425	-0.1667	-0.1394	-0.1384	0.043	0.0121	0	0	0	0	0.1953
Machine Eqp	-0.1857	-0.1731	-1.3463	0.9765	-0.0236	-0.0066	0.1667	0	0	0	0
Machine PsiDp	-5.7043	-5.318	30.2023	-36.4435	-0.726	-0.2037	0	0	0	0	0
Machine PsiQpp	3.7841	-5.27	0.6407	0.6364	-26.6942	18.1214	0	0	0	0	0
Machine Edp	0.3779	-0.5262	0.064	0.0635	6.4481	-9.1733	0	0	0	0	0
Exciter EField	0	0	0	0	0	0	-3.1847	3.1847	0	0	0
Exciter VR	5.9583	-74.526	-23.7484	-23.5901	-42.3027	-11.8717	-18	-5	-100	0	0
Exciter VF	0	0	0	0	0	0	-0.5143	0	-2.8571	0	0
Governor Governor Output	0	-250	0	0	0	0	0	0	0	-10	0
Governor Turbine Bowl	0	0	0	0	0	0	0	0	0	10	-10

Figure 4.6: A matrix for Machine 3

4.3 For WSCC 9 bus system With DFIG Integration at Bus-2

- **Case3:**

Sr. No.	Eigen Value Bus1	Eigen Value Bus2	Eigen Value Bus3
1	-0.0235 + j0.0000	0.0000 + j0.0000	-0.4246 - j0.5857
2	-0.4309 - j0.9074	0.0000 + j0.0000	-0.4246 + j0.5857
3	-0.4309 + j0.9074	0.0000 + j0.0000	-3.1287 + j0.0000
4	-1.9131 + j0.0000	0.0000 + j0.0000	-6.5418 + j0.0000
5	-3.2258 + j0.0000	-0.0837 + j0.0000	-5.1679 + j7.8674
6	-0.0371 + j4.6175	-0.2000 + j0.0000	-5.1679 - j7.8674
7	-0.0371 - j4.6175	-0.3139 + j0.0000	-0.4681 + j12.9329
8	-5.1652 - j7.8118	-0.4744 + j0.0000	-0.4681 - j12.9329
9	-5.1652 + j7.8118	-3.3333 + j0.0000	-14.0926 + j0.0000
10	-12.1425 + j0.0000	-6.6667 + j0.0000	-32.8940 + j0.0000
11	-22.4769 + j0.0000	-1.0907 - j11.7777	-36.9736 + j0.0000
12	-23.3263 + j0.0000	-1.0907 + j11.7777	
13	-35.4782 + j0.0000	-16.9336 + j0.0000	
14		-20.0000 + j0.0000	
15		-20.0000 + j0.0000	
16		-26.5938 + j24.4369	
17		-26.5938 - j24.4369	
18		-50.0000 + j0.0000	
19		-51.4519 + j0.0000	

Table 4.5: Eigen Values

Sr. No.	Frequency(Hz)	Damping(%)	Lambda
1	0.344	8.819	-0.1913
2	0.474	4.119	-0.1227
3	0.996	59.309	-4.6097
4	0.9	15.909	-0.9117
5	0.662	3.768	-0.1569

Table 4.6: Modal Analysis

Row Name	Machine Angle	Machine Speed w	Machine Eqp	Machine PsiDp	Machine PsiQpp	Machine Edp	Exciter EField	Exciter VR	Exciter VF	Governor Filter Output	Governor Desired Gate	Governor Gate	Governor Turbine Flow
Machine Angle	0	376.9911	0	0	0	0	0	0	0	0	0	0	0
Machine Speed w	-0.0626	-0.0497	-0.0133	-0.0276	0.0494	0.0087	0	0	0	0	0	-0.1789	0.3058
Machine Eqp	0.0011	-0.0097	-0.3231	0.2023	-0.0029	-0.0005	0.1116	0	0	0	0	0	0
Machine PsiDp	0.3777	-3.2254	32.3496	-35.3794	-0.9569	-0.1682	0	0	0	0	0	0	0
Machine PsiQpp	3.7875	1.3895	0.476	0.9902	-23.3583	19.4098	0	0	0	0	0	0	0
Machine Edp	0	0	0	0	0	-3.2258	0	0	0	0	0	0	0
Exciter EField	0	0	0	0	0	0	-3.1847	3.1847	0	0	0	0	0
Exciter VR	-2.176	-92.7911	-28.6679	-59.6293	-0.9661	-0.1698	-18	-5	-100	0	0	0	0
Exciter VF	0	0	0	0	0	0	-0.5143	0	-2.8571	0	0	0	0
Governor Filter Output	0	-20	0	0	0	0	0	0	0	-22.6667	-0.8	0	0
Governor Desired Gate	0	0	0	0	0	0	0	0	0	0.6667	0	0	0
Governor Gate	0	0	0	0	0	0	0	0	0	6.6667	2	-2	0
Governor Turbine Flow	0	0	0	0	0	0	0	0	0	0	0	11.8078	-11.8078

Figure 4.7: A matrix for Machine-1

Row Name	Machine Eq	Machine Ip	Exciter Vref	Exciter EqppCmd	Exciter Kpv	Exciter Kiv	Exciter Qord	Exciter Pmeas	Exciter PowerFilter	Exciter SpeedPI	Exciter POrd	Governor TurbineSpeed	Governor ShaftAngle	Governor GenSpeed	Governor GenDelta Angle	Stabilizer Pitch	Stabilizer PitchControl	Stabilizer PitchComp
Machine Eq	-30	0	0	30	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Machine Ip	-6.4897	-32.115	0	0	0	0	0	0	0	0	19.1766	0	0	0	0	0	0	0
Exciter Vref	-0.2041	-0.0637	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Exciter EqppCmd	-26.3088	-8.5739	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Exciter Kpv	0	0	0	0	-20	0	0	0	0	0	0	0	0	0	0	0	0	0
Exciter Kiv	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Exciter Qord	0	0	0	0	6.6667	6.6667	-6.6667	0	0	0	0	0	0	0	0	0	0	0
Exciter Pmeas	3.2902	22.7451	0	0	0	0	0	-20	0	0	0	0	0	0	0	0	0	0
Exciter PowerFilter	0.0209	0.1444	0	0	0	0	0	0	-0.2	0	0	0	0	0	0	0	0	0
Exciter SpeedPI	0	0	0	0	0	0	0	0	-0.6	0	0	0	0	0.6	0	0	0	0
Exciter POrd	0	0	0	0	0	0	0	0	-71.4667	23.8222	-20	0	0	83.6309	0	0	0	0
Governor TurbineSpeed	0	0	0	0	0	0	0	0	0	0	0	-0.2214	-0.0424	0.1735	0	0	0	0
Governor ShaftAngle	0	0	0	0	0	0	0	0	0	0	0	376.9911	0	-376.991	0	0	0	0
Governor GenSpeed	-0.1006	-0.6958	0	0	0	0	0	0	0	0	0	1.2146	0.2969	-0.8803	0	0	0	0
Governor GenDeltaAngle	0	0	0	0	0	0	0	0	0	0	0	0	0	376.9911	0	0	0	0
Stabilizer Pitch	0	0	0	0	0	0	0	0	0	0	8.1	500	0	0	0	-3.3333	3.3333	3.3333
Stabilizer PitchControl	0	0	0	0	0	0	0	0	0	0	0	25	0	0	0	0	0	0
Stabilizer PitchComp	0	0	0	0	0	0	0	0	0	0	24.3	0	0	0	0	0	0	0

Figure 4.8: A matrix for Machine-2

Row Name	Machine Angle	Machine Speed w	Machine Eqp	Machine PsiDp	Machine PsiQpp	Machine Edp	Exciter EField	Exciter VR	Exciter VF	Governor Governor Output	Governor Turbine Bowl
Machine Angle	0	376.9911	0	0	0	0	0	0	0	0	0
Machine Speed w	-0.4221	-0.2045	-0.2102	-0.2193	0.1301	0.039	0	0	0	0	0.1661
Machine Eqp	-0.1912	-0.1961	-1.8823	1.482	-0.0267	-0.008	0.1698	0	0	0	0
Machine PsiDp	-4.1576	-4.263	30.8805	-35.8925	-0.5801	-0.174	0	0	0	0	0
Machine PsiQpp	3.9678	-3.6743	0.4696	0.49	-24.9057	18.5283	0	0	0	0	0
Machine Edp	0.5915	-0.5478	0.07	0.073	9.2075	-11.8249	0	0	0	0	0
Exciter EField	0	0	0	0	0	0	-3.1847	3.1847	0	0	0
Exciter VR	2.2808	-64.4168	-22.0728	-23.0293	-34.3285	-10.2986	-18	-5	-100	0	0
Exciter VF	0	0	0	0	0	0	-0.5143	0	-2.8571	0	0
Governor Governor Output	0	-250	0	0	0	0	0	0	0	-10	0
Governor Turbine Bowl	0	0	0	0	0	0	0	0	0	10	-10

Figure 4.9: A matrix for Machine-3

4.4 For DFIG Integration With a Load Change of 50 MW at Bus-5.

- **Case4:**

Sr. No.	Eigen Value Bus1	Eigen Value Bus2	EigenValueBus2
1	-0.0235 + j0.0000	0.0000 + j0.0000	-0.4246 - j0.5857
2	-0.4309 - j0.9074	0.0000 + j0.0000	-0.4246 + j0.5857
3	-0.4309 + j0.9074	0.0000 + j0.0000	-3.1287 + j0.0000
4	-1.9131 + j0.0000	0.0000 + j0.0000	-6.5418 + j0.0000
5	-3.2258 + j0.0000	-0.0837 + j0.0000	-5.1679 + j7.8674
6	-0.0371 + j4.6175	-0.2000 + j0.0000	-5.1679 - j7.8674
7	-0.0371 - j4.6175	-0.3139 + j0.0000	-0.4681 + j12.9329
8	-5.1652 - j7.8118	-0.4744 + j0.0000	-0.4681 - j12.9329
9	-5.1652 + j7.8118	-3.3333 + j0.0000	-14.0926 + j0.0000
10	-12.1425 + j0.0000	-6.6667 + j0.0000	-32.8940 + j0.0000
11	-22.4769 + j0.0000	-1.0907 - j11.7777	-36.9736 + j0.0000
12	-23.3263 + j0.0000	-1.0907 + j11.7777	
13	-35.4782 + j0.0000	-16.9336 + j0.0000	
14		-20.0000 + j0.0000	
15		-20.0000 + j0.0000	
16		-26.5938 + j24.4369	
17		-26.5938 - j24.4369	
18		-50.0000 + j0.0000	
19		-51.4519 + j0.0000	

Table 4.7: Eigenvalues

Sr. No.	Frequency(Hz)	Damping(%)	Lambda
1	1	27.327	-1.7849
2	0.594	45.491	-1.908
3	0.352	60.005	-1.6567
4	0.049	-19.091	0.0597

Table 4.8: Modal Analysis

Row Name	Machine Angle	Machine Speed w	Machine Eqp	Machine PsiDp	Machine PsiQpp	Machine Edp	Exciter EField	Exciter VR	Exciter VF	Governor Filter Output	Governor Desired Gate	Governor Gate	Governor Turbine Flow
Machine Angle	0	376.9911	0	0	0	0	0	0	0	0	0	0	0
Machine Speed w	-0.0626	-0.0497	-0.0133	-0.0276	0.0494	0.0087	0	0	0	0	0	-0.1789	0.3058
Machine Eqp	0.0011	-0.0097	-0.3231	0.2023	-0.0029	-0.0005	0.1116	0	0	0	0	0	0
Machine PsiDp	0.3777	-3.2254	32.3496	-35.3794	-0.9569	-0.1682	0	0	0	0	0	0	0
Machine PsiQpp	3.7875	1.3895	0.476	0.9902	-23.3583	19.4098	0	0	0	0	0	0	0
Machine Edp	0	0	0	0	0	-3.2258	0	0	0	0	0	0	0
Exciter EField	0	0	0	0	0	0	-3.1847	3.1847	0	0	0	0	0
Exciter VR	-2.176	-92.7911	-28.6679	-59.6293	-0.9661	-0.1698	-18	-5	-100	0	0	0	0
Exciter VF	0	0	0	0	0	0	-0.5143	0	-2.8571	0	0	0	0
Governor Filter Output	0	-20	0	0	0	0	0	0	0	-22.6667	-0.8	0	0
Governor Desired Gate	0	0	0	0	0	0	0	0	0	0.6667	0	0	0
Governor Gate	0	0	0	0	0	0	0	0	0	6.6667	2	-2	0
Governor Turbine Flow	0	0	0	0	0	0	0	0	0	0	0	11.8078	-11.8078

Figure 4.10: A matrix for Machine-1

Row Name	Machine Eq	Machine Ip	Machine Vmeas	Exciter Vref	Exciter EqppCmd	Exciter Kpv	Exciter Kiv	Exciter Qord	Exciter Pmeas	Exciter PowerFilter	Exciter SpeedPI	Exciter POrd	Governor TurbineSpeed	Governor ShaftAngle	Governor GenSpeed	Governor GenDeltaAngle	Stabilizer Pitch	Stabilizer PitchControl	Stabilizer PitchComp
Machine Eq	-50	0	0	0	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Machine Ip	-10.816	-53.525	0	0	0	0	0	0	0	0	0	31.9609	0	0	0	0	0	0	0
Machine Vmeas	0	0	-50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Exciter Vref	-0.2041	-0.0637	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Exciter EqppCmd	-26.309	-8.5739	0	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Exciter Kpv	0	0	0	0	0	-20	0	0	0	0	0	0	0	0	0	0	0	0	0
Exciter Kiv	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Exciter Qord	0	0	0	0	0	6.6667	6.6667	-6.6667	0	0	0	0	0	0	0	0	0	0	0
Exciter Pmeas	3.2902	22.7451	0	0	0	0	0	0	-20	0	0	0	0	0	0	0	0	0	0
Exciter PowerFilter	0.0209	0.1444	0	0	0	0	0	0	0	-0.2	0	0	0	0	0	0	0	0	0
Exciter SpeedPI	0	0	0	0	0	0	0	0	0	-0.6	0	0	0	0	0.6	0	0	0	0
Exciter POrd	0	0	0	0	0	0	0	0	0	-71.467	23.8222	-20	0	0	83.6309	0	0	0	0
Governor TurbineSpeed	0	0	0	0	0	0	0	0	0	0	0	0	-0.2214	-0.0424	0.1735	0	0	0	0
Governor ShaftAngle	0	0	0	0	0	0	0	0	0	0	0	0	376.991	0	-376.99	0	0	0	0
Governor GenSpeed	-0.1006	-0.6958	0	0	0	0	0	0	0	0	0	0	1.2146	0.2969	-0.8803	0	0	0	0
Governor GenDeltaAngle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	376.991	0	0	0	0
Stabilizer Pitch	0	0	0	0	0	0	0	0	0	0	0	8.1	500	0	0	0	-3.3333	3.3333	3.3333
Stabilizer PitchControl	0	0	0	0	0	0	0	0	0	0	0	0	25	0	0	0	0	0	0
Stabilizer PitchComp	0	0	0	0	0	0	0	0	0	0	0	24.3	0	0	0	0	0	0	0

Figure 4.11: A matrix for Machine-2

Row Name	Machine Angle	Machine Speed w	Machine Eqp	Machine PsiDp	Machine PsiQpp	Machine Edp	Exciter EField	Exciter VR	Exciter VF	Governor Governor Output	Governor Turbine Bowl
Machine Angle	0	376.9911	0	0	0	0	0	0	0	0	0
Machine Speed w	-0.4221	-0.2045	-0.2102	-0.2193	0.1301	0.039	0	0	0	0	0.1661
Machine Eqp	-0.1912	-0.1961	-1.8823	1.482	-0.0267	-0.008	0.1698	0	0	0	0
Machine PsiDp	-4.1576	-4.263	30.8805	-35.8925	-0.5801	-0.174	0	0	0	0	0
Machine PsiQpp	3.9678	-3.6743	0.4696	0.49	-24.9057	18.5283	0	0	0	0	0
Machine Edp	0.5915	-0.5478	0.07	0.073	9.2075	-11.8249	0	0	0	0	0
Exciter EField	0	0	0	0	0	0	-3.1847	3.1847	0	0	0
Exciter VR	2.2808	-64.4168	-22.0728	-23.0293	-34.3285	-10.2986	-18	-5	-100	0	0
Exciter VF	0	0	0	0	0	0	-0.5143	0	-2.8571	0	0
Governor Governor Output	0	-250	0	0	0	0	0	0	0	-10	0
Governor Turbine Bowl	0	0	0	0	0	0	0	0	0	10	-10

Figure 4.12: A matrix for Machine-3

4.5 Analysis And Result

Insufficient damping torque resulting in oscillation of rotor at higher oscillation give rise to the small signal stability problem.
Eigen value analysis and modal analysis form the basis of system analysis for small signal stability studies.
The dynamic system i.e. the power system can be described by nonlinear differential equation as:

$$\dot{x} = f(x, u) \tag{4.1}$$

$$y = g(x, u) \tag{4.2}$$

Since, the disturbance considered is too small hence, for the purpose of analysis, linearization of the system equation is done. Hence, the linearized equation can be written as:

$$\Delta\dot{x} = A\Delta x + B\Delta u \tag{4.3}$$

$$\Delta y = C\Delta x + D\Delta u \tag{4.4}$$

The stability of the system is determined from the eigen values (λ) of the system state matrix **A**. Matrix **A** obtained from the load flow data is also termed as plant matrix or the Jacobin matrix as evident from the figure (4.1,4.2,4.3,4.4,4.5,4.6,4.7,4.8,4.9) of the four systems under consideration.
The eigen value(λ) obtained from the roots of the characteristic equation which is evident from table (4.1,4.3,4.5,4.7) is used to determine the stability of the system. The characteristic equation is given as:

$$det(A - \lambda I) = 0 \tag{4.5}$$

where,

$$\lambda = \sigma \pm j\omega \tag{4.6}$$

Frequency of oscillation is give as:

$$f = \frac{\omega}{2\pi} \tag{4.7}$$

For table 4.1, the maximum and minimum eigen values respectively are:
-0.0235 and -35.7701 for Bus-1
-0.3856 and -37.0327 for Bus-2
-0.4201 and -37.1571 for Bus-3
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-0.0235 and -35.7701 for Bus-1
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For table 4.1, the maximum and minimum eigen values respectively are:
-0.0235 and -35.4782 for Bus-1
-0.0837 and -51.4519 for Bus-2
-0.4246 and -36.9736 for Bus-3
For table 4.1, the maximum and minimum eigen values respectively are:
-0.0235 and -35.4782 for Bus-1
-0.0837 and -51.4519 for Bus-2
0.4246 and -36.9736 for Bus-3
Eigen value having negative real part says that the system is asymptotically stable, higher the magnitude of the negative real part, faster would be the damping of the system.
When at least one of the eigen values is having a positive real part, the system becomes unstable.
From table 4.5 and table 4.7 it can be observed that, Bus-2 has four zero eigen values, thus when the real parts of the eigen values are zero, it is not possible to comment on the basis of the first approximation.
The imaginary part of the eigen value is used to determine the frequency of oscillation.
Another important component which is taken under consideration is the **P** Participation Factor and the Left and the Right eigen vectors.

$$p_{ki} = \phi_{ki}\psi_{ik} \tag{4.8}$$

where,
(ϕ) is right eigen vector
(ψ) is left eigen vector
The participation factor will combine the left and the right eigen vector and it shows the participation of (k_{th}) state variable in the (i_{th}) mode and vice-versa.
From the modal analysis i.e table (4.2, 4.4,4.6) the damping ratio of the system is determined.
The damping ratio (ζ) is used to determine the decay rate of the amplitude of oscillation.
The damping ratio (ζ) is given by:

$$\zeta = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}} \tag{4.9}$$

Positive damping ratio indicates that the system after perturbation settles down at or near to its equilibrium point and a negative damping ratio indicates that the system continues to oscillate after being perturbed.
The analysis of the system also shows that after the inclusion of DFIG to the system, the modes of frequency changes and subsequently at certain modes of oscillation i.e table (4.8) at frequency 0.049 Hz, the system gives sufficiently high negative damping.
Hence, with the penetration of DFIG into the system, the modes of frequency changes and hence, tuning of PSS for this specific frequency is also required.

Chapter 5

Conclusion and Future Scope

5.1 Conclusion

As the wind turbine technology is getting more and more importance day by day, the type 3 wind turbine is replacing the existing conventional generator.
It is well known that excitation system of conventional generator is designed to generate positive synchronous and damping torque.
The PSS is tuned in such a way that it washes out the low frequency oscillation and advances the low frequency signal by lead lag compensator.
The base for PSS tuning is the number of turbines connected to rotor of generator and mode of frequencies which is directly calculated by state matrix. As the induction generator is replacing the existing synchronous generator, mode of frequency will change.
The main difference between conventional and DFIG machine is that one is working as constant voltage source and one is working as constant current source.
DFIG is not having any physical exciter (Some literature says that GSC and RSC can be treated as exciter). But there is no provision in DPC controller which can give certain amount of synchronous and damping torque. So the controllers are designed in such a way that the DFIG will behave as constant power source whose power tracking point will be decided by MPPT (provided that voltage across its terminal and wind speed velocity is constant).
The DFIG has been the major source of small signal oscillation as it is tracking the maximum power point. Due to the controller tracking characteristic and fluctuation in DC link voltage, the power output of DFIG will always vary in some specific interval even though load is not changing. This effect will introduce the oscillation in frequency.
If the change in wind speed is considered, it again becomes the major source of small signal oscillation (author has not touched this part in this thesis).
Due to reasons said above, the mode of frequency is changed after introducing DFIG in system.
The results clearly show that all the low frequency oscillations were having pos-

itive damping torque with conventional generators.After introduction of DFIG in standard system, some low frequency oscillation is having negative damping torque which suggests that the system might be unstable after long time. So the tuning of AVR and PSS has to be changed in order to make the system stable again.

5.2 Future Scope

AVR and PSS can be designed with proper tuning to damp out the negative damping that is associated with both conventional synchronous generator as well as the DFIG.

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