CHAPTER 1

INTRODUCTION

1.1 WIND ENERGY DEVELOPMENT IN INDIA

With the abundance of wind energy resources in many parts of the country, especially along the coastline, electricity generation through wind energy provides a viable and environmentally friendly option. In the 80's and 90's wind turbines were treated as small local power sources that were of negligible importance from a power system point of view. Now-a-days, thousands of megawatts of wind power, which are decentralized and spread over large extensions, are integrated to the grid. Thus, wind power cannot be treated as an "unimportant" power source anymore; since it represents a higher percentage of the total generation installed capacity.

Figure 1.1 reveals that currently India stands fifth in wind generation after China, U.S, Germany and Spain. At present, a large number of wind turbine generating systems are being planned around the country. As of June 2013, renewable energy accounted for 12.25 percent of total installed capacity, out of that 9 percent is contributed by newly installed wind turbines as shown in Figure 1.2 (WWEA Report 2013).

In 2011 the state-run Centre for Wind Energy Technology (CWET) reassessed India’s wind power potential as 1, 02,778 MW at 80 meters height. Over the past year, other research organizations have estimated wind potential using differing models for mapping the wind resource. In one such study conducted by the Lawrence Berkeley National Laboratory, assuming a turbine
density of 9 MW/km², the total wind potential in India with a minimum capacity factor of 20 percent varies from 2,006 GW at 80 meters hub-height to 3,121 GW at 120-meters hub-height.

Figure 1.1  India in world wind power

Figure 1.2  World wide installed capacity in 2013

The installable wind power potential of India as per the revised estimates of Ministry of New and Renewable Energy (MNRE) has been
assessed at around 92,092 MW at 80 meters height as of April 2012. The untapped installable wind power potential of India is around 73,541 MW as of April 2013, since 18,551 MW is already installed capacity as on 31st March 2013 (MNRE Report 2013). The state-wise installed capacity is presented in Table 1.1.

Table 1.1  State-wise installed capacity in MW as on March 2013

<table>
<thead>
<tr>
<th>Sl.No.</th>
<th>State</th>
<th>Capacity in MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Tamil Nadu</td>
<td>7154</td>
</tr>
<tr>
<td>2</td>
<td>Gujarat</td>
<td>3093</td>
</tr>
<tr>
<td>3</td>
<td>Maharashtra</td>
<td>2976</td>
</tr>
<tr>
<td>4</td>
<td>Rajasthan</td>
<td>2355</td>
</tr>
<tr>
<td>5</td>
<td>Karnataka</td>
<td>2113</td>
</tr>
<tr>
<td>6</td>
<td>Madhya Pradesh</td>
<td>386</td>
</tr>
<tr>
<td>7</td>
<td>Andhra Pradesh</td>
<td>435</td>
</tr>
<tr>
<td>8</td>
<td>Kerala</td>
<td>35</td>
</tr>
<tr>
<td>9</td>
<td>Others</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong></td>
<td><strong>18551</strong></td>
</tr>
</tbody>
</table>

Potential windy locations have been identified in the flat coastal terrains in Tamilnadu, Kerala, Gujarat, Lakshadweep, Andaman and Nicobar Islands, Orissa and Maharashtra. Favorable sites have also been identified in some inland locations of Karnataka, Andhra Pradesh, Madhya Pradesh, West Bengal, Uttarakhand and Rajasthan. Sixty three districts are identified as potential districts totally in India. There are 506 wind monitoring stations established till July 2012.

On the other hand, Government is looking to prepare a time-bound action plan for development of offshore wind energy. Policy and guidelines for offshore wind are likely to be announced by the Ministry of New and Renewable Energy in the near future. According to CWET, as per the
preliminary assessment conducted by the Scottish Development International (SCI), Tamil Nadu has a potential of about 1 GW in the north of Rameswaram and another 1 GW in the south of Kanyakumari. In a recent study conducted by WISE, the offshore wind potential of Tamil Nadu has been estimated as 127 GW at 80 meters height, which will need further validation.

In India, previous regulations under the Indian electricity grid code (IEGC) did not allow renewable based power to connect to the inter-state transmission network. The Central Electricity Regulatory Commission (CERC) recently allowed projects with capacities of over 50 MW to connect directly to the central transmission network subject to scheduling requirements. This allowance has addressed one long-standing concern of investors by reducing the threat of curtailment. Under (IEGC) 2010, wind and solar projects have been offered ‘must-run’ status.

Therefore, with the change in the focus of government policy, wind energy sector is witnessing a progressive trend as shown in Figure 1.3. India’s electricity demand is projected as three times of 2005 in 2030. In the recently released National Electricity Plan the Central Electricity Authority projected the need for 350-360 GW of total generation capacity by 2022.

Figure 1.3  Indian wind installation- an advanced scenario
1.2 CLASSIFICATION OF WECS

There are basically three types of generators that are commonly used with commercial wind turbines. They are (1) fixed-speed wind energy conversion systems (FSWECS) (Type-1 wind turbines) (2) partially variable-speed wind energy conversion systems (PVWECS) (Type-2 wind turbines) (3) variable-speed wind energy conversion systems (VSWECS) based on doubly-fed induction generator (DFIG) (Type-3 wind turbines) and permanent magnet synchronous generator (PMSG) (Type-4 wind turbines).

1.2.1 Type-1 Wind Turbines

A fixed-speed turbine consists of a rotor and a squirrel-cage induction generator (SCIG), connected via a gearbox as shown in Figure 1.4 (Munteanu et al 2008). The generator stator winding is connected to the grid. The generator slip varies with the generated power, so the speed is not, in fact, constant. However, as the speed variations are very small (just 1-2%), it is commonly referred to as a 'fixed-speed' turbine.

![Figure 1.4 Structure of Type-1 wind turbines](image)

A squirrel-cage generator always draws reactive power from the grid, which is undesirable, especially in weak networks. The reactive power
consumption of squirrel-cage generators is therefore nearly always compensated by capacitors. An anti-parallel thyristor soft-start unit is used to build up the magnetic flux slowly, in order to minimise the transient current during energisation of the machine.

Fixed-speed WECS has the advantage of being simple, robust and reliable, with simple and inexpensive electric systems and well proven operation. On the other hand, due to the fixed-speed operation, the mechanical stress is significant. All fluctuations in wind speed are transmitted into the mechanical torque and further, as electrical fluctuations, into the grid. Furthermore, fixed-speed WECS have very limited controllability (in terms of rotational speed), since the rotor speed is fixed, almost constant and stuck to the grid frequency.

1.2.2 Type-2 Wind Turbines

An evolution of the fixed-speed WECS are the limited variable speed WECS. They are equipped with a wound-rotor induction generator (WRIG) with variable external rotor resistance as shown in Figure 1.5 (Munteanu et al 2008). The unique feature of this WECS is that it has a variable additional rotor resistance, controlled by power electronics. Thus, the

Figure 1.5 Structure of Type-2 wind turbines
total (internal plus external) rotor resistance is adjustable, further controlling the slip of the generator and therefore the slope of the mechanical characteristic. Obviously, the range of the dynamic speed control is determined by how big the additional resistance is. Usually the control range is up to 10% above the synchronous speed.

1.2.3 Need of Variable Speed WECS

Variable-speed wind turbines provide the following key advantages:

1) They are cost effective and provide a simple pitch control. At lower wind speed, the pitch angle is usually fixed. Pitch angle control is performed only to limit maximum output power at high wind speeds.

2) They reduce mechanical stresses. Wind gusts can be absorbed, i.e., energy is stored in mechanical inertia of the turbine that reduces torque pulsations.

3) They dynamically compensate for torque and power pulsations caused by tower shadow effect. The tower shadow effect causes large torque pulsations at a rate equal to the turbine rotor speed times the number of rotor blades.

4) They reduce the electrical flicker and hence improve the power quality.

5) Turbine speed is adjusted as a function of wind speed to maximize output power. Operation at maximum power point can be realised over a wide power range. Thus they improve system efficiency.
6) They reduce the acoustic noise because low speed operation is possible at low power conditions.

1.2.3.1 Type-3 wind turbines

A typical configuration of DFIG wind turbine is shown in Figure 1.6 (Jayashri 2007). It uses a wound-rotor induction generator with slip rings to take current in or out of the rotor winding. The variable-speed operation is obtained by injecting a controllable voltage into the rotor at slip frequency. The rotor winding is fed through a variable frequency power converter. The power converter decouples the network electrical frequency from the rotor mechanical frequency, enabling variable-speed operation of the wind turbine. A DFIG system can deliver power to the grid both through the stator and rotor, when operated at super-synchronous mode.

![Figure 1.6 Structure of Type-3 wind turbine](image)

1.2.3.2 Type-4 wind turbines

The variable-speed wind turbine with permanent magnet synchronous generator is schematically shown in (Munțeanu et al 2008)
Figure 1.7. The aerodynamic rotor and generator shafts are generally coupled directly, without a gearbox. The generator is a multi-pole synchronous generator designed for low speeds (Miller 1989). The generator can be either an electrically excited synchronous generator or a permanent magnet generator. To permit variable-speed operation, the synchronous generator is connected to the grid through a variable frequency power converter, which completely decouples the generator speed from the grid frequency. Therefore, the electrical frequency of the generator may vary as the wind speed changes, while the grid frequency remains unchanged.

![Figure 1.7 Structure of Type-4 wind turbines](image)

The advantages of a PMSG configuration are 1) gearless construction; 2) the elimination of a dc excitation system; 3) full controllability of the system for maximum wind power extraction and grid interface; and 4) ease in accomplishing fault-ride through and grid support. The synchronous nature of PMSG may cause problems during start-up, synchronization and voltage regulation and they need a cooling system, since the magnetic materials are sensitive to temperature and they can loose their magnetic properties if exposed to high temperatures (Ackermann 2005).
Comparing the two variable-speed designs (Type-3 and Type-4 wind turbines), one advantage that can be observed in designs based on the DFIG, is that they use a small rating of power electronics converter since it is implemented in rotor whereas in the PMSG based WECS a larger electronic converter is used as the full 100% of the power generated has to pass through it. But the main drawback of DFIG systems when compared with direct-drive variable-speed turbines is that they still need a rather maintenance intensive and potentially unreliable gearbox in the drive-train.

1.3. NEED FOR STABILITY ANALYSIS

Large penetration of distributed generation as explained in section 1.1, would have far reaching consequences, not only on the distribution network but also on the transmission grid and the rest of the generators. Before installing wind generators, utility engineers must analyze the worst operating scenarios to guarantee that the power system will not be adversely affected by the wind generators.

Since WECS in use today are not synchronously connected to the grid they will not themselves cause electromechanical modes of oscillation. However, the introduction of large amounts of wind generation does have the potential to indirectly change the damping performance of the system by

i. significantly altering the dispatch of synchronous generation in order to accommodate wind generation;

ii. significantly altering the power flows in the transmission network; and

iii. interacting with synchronous machines to change the damping torques induced on their shafts.
The first two of these factors are largely independent of the WECS technology. The third factor depends on the dynamic performance characteristics of the turbine generator and on other relatively fast acting wind farm controls (e.g. STATCOMs which may be installed for voltage control purposes).

The majority of the wind turbines installed in India are FSWECS. They are equipped with an induction generator that is directly connected to the grid with a soft-starter and with a shunt capacitor bank for reducing reactive power compensation. These generators require reactive power from the grid for excitation. One important thing to be noted here is the reactive power consumption of induction generator increases with wind velocity. In addition to that, increase in wind turbines further makes the situation worse. It is clear that real power generation and reactive power absorption are increasing with the increase in number of turbines. It results in voltage drop at point of common coupling (PCC).

As the penetration of wind power in electrical power system increases, the behaviour of wind turbine under faults, voltage dips and wind speed variations becomes more important. In FSWECS the fluctuations in the wind speed are transmitted as fluctuations in the mechanical torque and then in the electrical output power to the grid (Rahimi & Mostafa 2009). Thus, it is essential to investigate the effect of a large penetration of distributed generation on the stability and security of the power system.

This thesis conducts small signal stability (eigenvalue) analysis on grid connected WECS. Different combinations of Type-1, Type-2 and Type-4 wind turbines are considered for the study. Analysis is performed for different penetrations of wind power by changing number of wind turbines and wind velocity.
1.4. LITERATURE SURVEY

1.4.1 Literature Survey on Small Signal Stability Analysis of Grid Connected Fixed Speed WECS

Nomikos & Vournas (2005) investigated power system small-signal stability, considering induction machines as dynamic elements. In this study, a linearized model for a multi-machine system that includes both synchronous and induction machines is presented. This linear model is used to explain the small signal dynamic behavior of small and large induction machines and to identify the critical parameters that determine the type of their response. The inertia and the rotor open circuit time constant are found to be the most critical parameters in this respect. This analysis also allowed the approximate estimation of eigenvalues for large and small induction machines.

It was also shown that when replacing identical induction machines connected in parallel with a single aggregate machine, the dominant dynamics are preserved, while the interaction modes, which are neglected in the equivalent, are in general more stable. It was found that the impact of load modeling on PSS design becomes significant when the system mode was involved.

Tabesh & Iravani (2006) introduced a small-signal dynamic model of a fixed-frequency induction machine based wind farm connected to an electrical power system. The model represents the system small-signal dynamics in the frequency range of a fraction of Hz to 50-60 Hz. Based on the proposed model, performance indices are introduced to i) investigate sensitivity of the system modes, e.g., torsional modes, to the system parameters, and ii) evaluate the system capability to reject electrical and mechanical disturbances, e.g., a wind gust. The application of the model to the analysis of a system with two wind units are presented and the study
results are validated based on comparison with the time-domain simulation results obtained in the PSCAD/EMTDC environment.

The study results show that:

1. The electrical disturbances, e.g., a temporary three-phase fault, can excite torsional modes of the wind turbine-generator. Thus, a reduced-order model of the wind farm based on a single-mass representation can cause erroneous results.

2. The low-frequency mechanical disturbances, e.g., a wind gust, merely excites the inertial modes and not the torsional mode. Hence, for low-frequency analysis (about 0.1 Hz), using a single-mass model for a wind turbine-generator is a valid representation.

3. For evaluating the system disturbance rejection capability in a multi-machine system, the norm-based performance indices provide more reliable and accurate results in comparison to the eigenvalues of the system.

4. The electromechanical dynamics of the wind units are coupled through the electrical network, i.e., the collector and the utility grid. Therefore, any mechanical or electrical disturbance that perturbs one wind unit excites the oscillatory modes of the other units.

Fernandez et al (2007) dealt with the impact of wind farms on the network frequency dynamics and on its control. The following cases were considered: constant speed wind farms with SCIG, variable speed wind farms with DFIG operating at constant power, with proportional frequency control
and with proportional plus derivative frequency control. A comparative analysis of the dynamic behavior of a test power system for the different cases was based on the change of the location of eigenvalues as wind power penetration is increased. In order to emphasize considerations under study, a broad span of wind penetrations was evaluated. It was observed that some of the calculated eigenvalues were particularly sensitive to the wind penetration increments. Then, a participation factor calculus allowed relating these eigenvalues with the network frequency. It was shown that:

1. Fixed speed SCIG farms and variable speed DFIG farms with frequency control increased the eigenvalues damping, improving the dynamic response of the frequency.

2. This improvement was more significative in DFIG farms with frequency control.

3. The oscillatory eigenvalues damping increased with the wind penetration.

4. The wind farm contribution reduced the transient power demand of the synchronous generator.

Vowles et al (2008) assessed the impact of increasing the amount of wind generation on the damping performance of the New Zealand power system. A comparison is made between the damping performance of (i) a base case scenario which has no wind generation (except for existing wind farms) and (ii) a corresponding scenario in which wind generation is introduced to the system by displacing an equivalent amount of synchronous generation. The accommodation of very high levels of wind generation will most probably require a number of changes in the structure and operation of the system. It is possible that such changes will have a consequential effect on the damping-performance of the system.
The conclusions of this investigation are summarized below.

1. For the South Island system, varying the synchronous generation which is displaced to accommodate the wind generation has a relatively minor effect on the damping of the dominant mode.

2. High levels of wind generation may result in significant changes in network power flows resulting in greater network congestion than would otherwise have occurred. The increased congestion may result in significant degradation in the damping performance of the system.

Ulianov et al (2008) presented the small signal stability analysis of squirrel cage induction generator with model presented by Kundur (1993). The modeling and simulation is done with Matlab and a toolbox for stability purposes, called PSAT (Power System Analysis tool box). It is found that after disturbance (changes in wind speed, load demand and generator voltages), constant speed wind turbine system remains stable. It is suggested that further research must concentrate on multi-machine systems.

Li et al (2010) examined the impact of the increased penetration of squirrel cage induction generator based WECS on small signal stability for a single machine infinite system. It is showed that with the increment in penetration of these turbines, power system will experience a change in dynamics and operational characteristics. Reactive power compensation equipment SVC is introduced to enhance wind farm voltage stability. Eigenvalue analysis of three different scenarios is performed to give an intuitive understanding of the wind machine features.
• Case A: wind machine in infinite bus system is replaced by conventional round rotor synchronous machines with equivalent MVA rating.

• Case B: Induction generators with fixed capacitors connected to an infinite bus system.

• Case C: Induction generators with SVC connected to an infinite bus system.

The results indicate that effect on damping performance varies with circumstances. Time domain simulation conducted at the last part, effectively verified the conclusion received from frequency domain.

Yuanzhang et al (2010) provided an overview of recent progresses on the impact of the integration of large amounts of wind power on power system small signal stability and corresponding control strategies to enhance small signal stability. The influence of wind turbine generators on power system damping is analyzed qualitatively by modal analysis and time-domain simulations. Since the damping from WECS with basic power and voltage controllers alone is inappreciable, a variety of auxiliary controllers to amend small signal stability are summarized. Most of these controllers are implemented in VSWECS employing either Active Power Modulation-based PSSs (APM PSSs) or Reactive Power Modulation-based PSSs (RPM PSSs) method.

At present, it is universally accepted that constant speed WECS have a positive effect on the damping while for variable speed WECS, impact is much debatable. Future scope left to the researchers in the literature is coordination with different damping controllers.
Mendonça & Lopes (2005) dealt with the problem of large wind power integration and its potential impact on systems small signal stability. The adopted approach consisted in considering a test system and generating a representative data set of different system operating conditions like network configuration, load level, wind power integration levels, wind power dispersion, and unit commitment of conventional units. The data set is first analyzed to identify the driving forces that influence damping. Then some operation points are selected for a more detailed study, using modal analysis, to track the evolution of the oscillation modes when wind power is increased. This approach allows studying all possible operating scenarios, avoiding in that way a biased analysis.

Nonlinear time domain simulations are carried out using PSS/E software package on a modified test system with three areas (Kundur 1993). Although wind generation is, in general, not worsening damping regarding inter area oscillations, the changes in the operational structures of the systems may lead to considerable reduction on the damping of these modes. It is then observed that damping is reduced when wind power increases and contributes to congest weak interconnection lines. Inter area modes are the most sensitive ones.

Hossain et al (2011) investigated critical issues that limit the large-scale integration of wind generators and voltage compensation. Wind generators have more intermittent characteristics and lower inertial response. This changing nature of a power system has considerable effect on its dynamic behaviour resulting in power swings, dynamic interactions between different power system devices and less synchronized coupling.

Modal analysis, participation factors, eigenvalue tracking and dynamic simulations have been used to analyze the nature of system behaviour under large scale wind turbine and flexible AC transmission
systems (FACTS) device integrations. It is concluded that high compensation reduces the security limit under certain operating conditions and modes related to operating slip and shaft stiffness are most critical. They may limit the large scale integration of wind generation.

Rahimi & Mostafa (2009) have analytically investigated the dynamic behaviour of fixed speed wind turbines under wind speed fluctuations. The study of dynamic behaviour included modal and sensitivity analysis, dynamic behaviour analysis under wind speed fluctuation and eigenvalue tracking. They conclude that the dominant dynamics for dynamic/transient studies in FSWECs are the multi-mass mechanical dynamics and single mass representation of wind turbine rotor is inadequate for its dynamic and transient analysis, and yields incorrect indication of stability. On the other hand, electrical dynamics of stator, network and capacitor can be ignored without significant error on FSWECs dynamic behaviour.

Burnham et al (2009) described the operation of induction generator with variable rotor resistance control used in a wind turbine, to control the output power beyond the rated wind velocity. However, this method is less flexible than doubly fed induction generator. But, this method does not require the use of slip rings.

Tohidi et al (2010) describe modeling and small signal analysis of a grid connected fixed speed wind turbine generator. A complete model of FSWECs is derived and some reduced-order models are deduced. Eigenvalues and participation factors of the system for these models are calculated. Then, using the eigen analysis results, the models are compared and the simplifying assumptions which have been considered in the literatures are evaluated. Six models have been presented for studying the dynamic behavior of grid connected FSWECs.
Shawn et al (2012) discussed small signal stability analysis of a grid connected fixed speed wind turbine driven induction generator (IG) including series dynamic braking resistor (SDBR). The stator windings of IG are directly connected to a power grid thorough a step-up transformer and transmission line, where SDBR is dynamically inserted in the generation circuit for short time during network disturbance. A detailed mathematical model of IG, transmission line, SDBR and grid is employed to derive the complete dynamic equation of the studied system.

The purpose of SDBR is to mitigate the destabilizing depression of electrical torque and power during disturbance period. The power system small signal stability analysis is carried out using eigenvalue analysis. Modal and sensitivity analyses, participation factors are carried out to discover the relations between the modes and state variables. Small signal analysis of the dynamic behavior of fixed speed wind generator under voltage dip conditions with and without considering SDBR are verified by a time domain simulation model developed in MATLAB/SIMULINK.

Loo et al (2013) presented a mathematical modeling of synchronous and induction generators for wind turbines using state-space representations. Emphasis is given to those models suitable for control schemes of variable-speed wind turbines and their application for different power system studies. The state-space representations provide a convenient way to assess different configurations of fixed and variable-speed wind turbines based on synchronous and induction generators.

Typical system studies that are often employed to assess the impact of wind generation have been carried out using the models. In particular, the fault-ride through capability and behavior under three-phase faults has been evaluated for different wind turbine technologies through simulations in MATLAB/Simulink.
From the simulation results, it can be seen that both the SCIG and DFIG wind turbines are capable of satisfying grid code requirements. However, in the case of a DFIG wind turbine, a crowbar is required to limit the rotor currents within the capabilities of power electronics converters. An eigenvalue small-signal analysis showed that the FSIG and DFIG are stable for a weak network. Stability is preserved for higher short circuit levels, as expected.

1.4.2. Literature Survey on Small Signal Stability Analysis of Grid Connected PMSG based WECS

Westlake et al (1996) described a novel permanent-magnet synchronous generator for a wind turbine. The small pole pitch of the generator allows it to operate at low speeds. It can be directly coupled to the wind turbine and maintain a direct electrical grid connection. The ability to couple the generator directly to the wind turbine eliminates the need for the usual gearbox, but leads to a generator design where conventional damper windings are ineffective as there is too little space.

An alternative damping system is described whereby the stator is allowed limited rotational movement by connecting it to the wind turbine housing via a spring and a mechanical damper. This arrangement allows greater damping of power-angle oscillations than is possible using conventional damper windings. The response of the generator to step changes in driving torque is used to illustrate the effectiveness of such a design. The behavior of the generator on both synchronization and during operation in a varying wind is discussed to demonstrate the design feasibility.

Chinchilla et al (2006) described the operation and control of the PMSG based WECS. This system is connected to the power network by means of a fully controlled frequency converter, which consists of a pulse
width-modulation (PWM) rectifier, an intermediate dc circuit, and a PWM inverter. The generator is controlled to obtain maximum power from the incident wind with maximum efficiency under different load conditions. Vector control of the grid-side inverter allows power factor regulation of the windmill. Different experimental tests in a 3-kW prototype have been carried out to verify the benefits of the proposed system.

Rawn et al (2007) designed a controller that isolates wind-power fluctuations from the power grid. A linearized analysis was used to calculate how a small filter time constant can be implemented to obtain regulation of the tip-speed ratio for the widest range of frequencies. The methodology thus offers the possibility to either deliver a filtered power at suboptimal conversion efficiency or track peak wind power. It is mathematically demonstrated that the control structure achieves the regulation of torsional dynamics and the dc-link capacitor voltage without involving the grid-side converter controls, thus eliminating the influence of those dynamics on the grid. Also it is suggested that in today’s wind installations, providing a filtered power may not yield a monetary value that can compensate the economic losses associated with decreased energy capture.

Grabic et al (2008) proposed an energy conversion system for a wind turbine. The system comprises a grid connected PMSG, a small series converter (20% of rated power) in the star point of the open winding PMSG and an optional gearbox (GB). It is demonstrated that power electronic converter located in the star point of the PMSG of the wind turbine can be used to enable the direct connection of such system to the fixed frequency grid. The series converter provides damping to the system in case of input power and/or grid disturbances. Converter output voltage is controlled to provide damping, active resistance and to control its dc link voltage. The proposed control law comprises three components: the damping component,
the active resistance based compensator component and the dc bus voltage control component. It is concluded that the solution can be a basis for a new class of small and medium size fixed speed wind turbines equipped with permanent magnet generators.

Enamul et al (2010) presented a novel control strategy for the operation of a PMSG based stand-alone variable-speed wind turbine. The control strategy for the generator-side converter with maximum power extraction is presented. The stand-alone control is featured with output voltage and frequency controller that is capable of handling variable load. The excess power is dissipated in the dump-load resistor with the chopper control, and the dc-link voltage is maintained. Small-signal analysis which includes DC bus dynamics is presented. Simulation results show that the controllers can extract maximum power and regulate the voltage and frequency under varying wind and load conditions. The controller shows very good dynamic and steady-state performance.

Geng et al (2011) proposed an active-damping strategy for the suppression of speed and torsional oscillations in PMSG based WECS. Direct driven configuration with PMSG for WECS has many advantages. One of them is that the PMSG allows a small pole-pitch design, which reduces the generator diameter and is therefore cost-effective. However, because no damper is included in the design, torsional vibration and speed oscillations appear when the generator is directly connected to the wind turbine. Based on small-signal analysis, a low-bandwidth design for the power or generator torque controller of PMSG can help to reduce the oscillation amplitude, but the system dynamic performance is thus sacrificed. From the power-flow’s point of view, the oscillation is reflected in the dc-link current. With the help of switch function modelling based on the space-vector-modulation scheme,
the average dc-link current can be estimated and applied to the compensation strategy, which provides positive damping resulting in stability improvement.

Geng & Xu (2011) discussed the stability issues of the PMSG based direct driven WECS and presents a torque compensation strategy based on dc-link current estimation of the converters for the stability improvement. Because no damper is included in the design, torsional vibration and speed oscillations appear when the generator is directly connected to the wind turbine, which leads to instability issues. A slow generator torque controller can help to reduce the oscillation amplitude and improve the system stability but the capability is limited and it may affect the power response of the WECS. In contrast, the torque compensation strategy can be employed to provide positive damping of the oscillations. The torque compensation strategy contains a feed-forward compensator in the torque control loop, which is formulated based on the dc current injected into the dc link capacitor of the converters. With such compensation, the oscillatory mode is effectively suppressed and resulting in the improvement of small signal and transient stabilities of the WECS.

Vittal et al (2012) explored the relationship between wind generation, particularly the control of reactive power from variable speed wind turbine generators, and the rotor angle stability of the conventional synchronous generators in the system. The asynchronous nature of wind generation places an increased responsibility on conventional synchronous generation to provide the necessary resources to mitigate a contingency event. It is shown that the rotor angle of synchronous generators is directly influenced by the type of reactive power control employed by the wind generation. The implementation of appropriate control strategies in wind farms, particularly the implementation of terminal voltage control, can lessen the reactive power requirements of conventional synchronous units and help
mitigate large rotor angle swings and aid conventional generation in damping the oscillatory signal following a loss of generation event.

Knuppel et al (2012) presented a comprehensive analysis, which assesses the impact of full-load converter interfaced wind turbines on power system small-signal stability, that is, participation in power system oscillations, was investigated. A detailed WT model with all grid relevant control functions is used in the study. The system is analysed for the wind power plant (WPP) with and without a park-level voltage controller. The analysis is based on a seven-generator network, which illustrates some aspects of the dynamic behaviour of the UK power system, namely inter-area oscillations between major areas of the system. The study is based on modal analysis which is complemented with the time-domain simulations on the non-linear system. The analysis is repeated for various wind power penetration levels, different wind conditions, and with the WPP in power curtailment mode. The impact of selected wind turbines and WPP control parameters were investigated through parameter sensitivity analysis.

The study found that the inter-area modes were largely unaffected by the increased capacity of the WPP, with the modal characteristics being almost unchanged. From the sensitivity analysis, it was found that the local and the park level voltage controllers had the largest impact on the dominant inter-area mode, while only a limited impact was found for the active power and the pitch controllers. The participation in the system oscillatory modes of the WPP’s mechanical system was found to be orders of magnitudes smaller than those of the synchronous generators mechanical system. The very low participation factors imply that the WPP does not interact with these system modes.

Huang et al (2012) analyzed the stability of wind turbine with direct drive permanent magnet synchronous generator connected to power
grid after suffering a small disturbance and effectively designing the controllers’ parameters. This work builds a complete small-signal model of the wind turbine with direct drive PMSG connected to power system, which is composed of wind turbine, PMSG, back-to-back converters, controllers and power grid. Small signal stability analysis of power system is performed under parameter variations according to the traces of eigenvalues which helps to design controllers’ parameters. Simulation results show that the system is stable after suffering small disturbance of a wind velocity step response, and the system dynamic responses are consistent with the result of small-signal analysis.

Alizadeh & Yazdani (2013) proposed a simple real power control strategy, which augments the MPPT feature of modern WECSs, and is based on rapid torque control as opposed to the traditional pitch-angle control. This work presents the implementation of the proposed control strategy for a direct-drive WECS that employs the permanent-magnet synchronous generator. This work also presents a parameter-tuning procedure for the proposed control strategy. The effectiveness of the proposed control strategy is demonstrated through mathematical analysis and time-domain simulation studies.

Geng et al (2011) proposed a unified power control strategy for PMSG based WECS operating under different grid conditions. The conventional control strategy is mainly designed to promise the proper operation of the generator. In the strategy, the generator torque (power) is directly controlled while the grid side power is indirectly regulated. The disturbance at the generator side will aggravate the power responses at the grid side, which is not desired by the power system operator. The basic idea of the strategy is to first satisfy the power system requirements under different grid conditions.
In this strategy, the generator-side converter is used to control the dc-link voltage and the grid-side converter is responsible for the control of power flow injected into the grid. The generator-side controller has inherent damping capability of the torsional oscillations caused by drive-train characteristics. The grid-side control is utilized to satisfy the active and reactive current (power) requirements defined in the grid codes, and at the same time mitigates the current distortions even with unsymmetrical grid fault. During grid faults, the generator-side converter automatically reduces the generator current to maintain the dc voltage and the resultant generator acceleration is counteracted by pitch regulation.

Uehara et al (2011) presented an output power smoothing method by a simple coordinated control of DC-link voltage and pitch angle of a wind energy conversion system with a PMSG. The WECS adopts an AC-DC-AC converter system with the voltage-source converters (VSC). The proposed control schemes include a maximum power point tracking (MPPT) control. The DC-link voltage command is determined by adding the rated DC-link voltage with a simple smoothing index, which is based on the output power fluctuations of the PMSG. The output power fluctuations of low and high-frequency components are smoothed by the pitch angle control of the WECS, and the DC-link voltage control, respectively. By this method, the wind turbine blade stress is mitigated as the pitch action in high-frequency domain is reduced. In addition, the DC-link capacitor size is reduced without the charge/discharge action in low-frequency domain.

Li et al (2012) investigated both the conventional and a novel vector control mechanism for a PMSG wind turbine that has two side-by-side voltage source pulse width modulation converters. The proposed approach was based on a direct current vector control mechanism for control of both machine and grid-side converters of a PMSG wind turbine. Then, an optimal
control strategy was developed for integrated control of PMSG maximum power extraction, reactive power, and grid voltage support controls. Comprehensive simulation studies demonstrate that a PMSG wind turbine, based on the direct-current vector control structure, can effectively accomplish the wind turbine control objectives with superior performance within the physical constraints of the system under both steady and variable wind conditions. Beyond the physical constraints of a PMSG system, the proposed control approach operates in an optimal mode by controlling the machine side converter (MSC) for maximum wind power extraction as the first priority and controlling the grid side converter (GSC) to stabilize the dc-link voltage as the main concern.

Lopes et al (2010) presented a novel methodology for tuning proportional-integral (PI) controllers gains for the grid-side converter of direct-drive synchronous wind generator using a genetic algorithm (GA) approach. The control approach aims to improve the behavior of the direct-current (DC)-link voltage, by a more effective contribution of direct-drive wind generator controllers to the system controllability when an electrical fault occurs. The time-domain simulations are carried out using the single-machine infinite bus system model with one direct-drive synchronous generator. The performance of the wind generator with optimized controller parameters and with the parameters designed by the pole placement technique are compared to demonstrate that the control performance of the system.

Rodrigues et al (2013) introduced a structured multi-objective optimization process in the control structure of a PMSG applied in wind energy. A small-signal model is derived for the PMSG and the full rated voltage-source converters (VSCs) connected in a back-to-back arrangement. Thereafter, the linear model is used in a multi-objective genetic algorithm (MOGA) to fine-tune the proportional and integral (PI) gains of the both
machine and grid side converters control structure. A varying wind velocity profile with respect to time is given as input and time responses are obtained. It is found that the system is stable when using the gains that are obtained with the MOGA and performs well in the conducted case study.

1.4.3 Literature Survey on Response Surface Methodology (RSM)

RSM is a powerful statistical tool used to obtain an empirical model by finding the relationship between the design variables and response through statistical fitting method. The response can be obtained from real experiments or computer simulation. RSM is well adapted to develop an analytical model from which an objective function with constraints can be easily created. This optimization problem can be solved using an appropriate mathematical algorithm. So, the computation time is highly saved by using this method.

Park et al (2006) dealt with the optimum rotor design solution on torque ripple reduction for a synchronous reluctance motor with concentrated winding using response surface methodology. RSM had been recognized as an effective optimization approach for modeling performance of electrical devices using statistical fitting methodology. The RSM is achieved to use the experimental design method in combination with finite element method (FEM). It is well adapted to make analytical model for a complex problem considering a lot of interaction of design variables.

Sathavornvichit et al (2006) determined the optimal factors of flux Cored Arc Welding process for Steel ST37 using RSM. The process variables current, voltage, stick out and angle of welding are selected as independent variables. Tensile of weldment is expressed as a function of independent variables, using second order polynomial. The experimental values for tensile of weldment under different treatment conditions are presented. The statistical
analysis indicates that the model is adequate, possessing no significant lack of fit.

Bradley (2007) discussed in detail on designing, modeling, and analyzing the Response Surface Methodology. The three types of Response Surface Methodology, the first-order, the second-order, and three-level fractional factorial, are explained and analyzed in depth. A first-order model is appropriate for describing a flat surface with or without tilted surfaces and a second-order model is suitable for describing quadratic surface. The central composite design is the popular method to conduct a second-order design.

The factorial designs are widely used in experiments when the curvature in the response surface is concerned. All treatment factors have 3-levels in the three-level factorial design. This design is more efficient, it allows collecting information on the main effects and on the low-order interactions.

After an appropriate design is conducted, the response surface analysis can be done by any statistical computer software and then statistical analyses can be applied to draw the appropriate conclusions. The thesis also provides examples of application of each model by numerically and graphically using computer software.

Hasanien et al (2010) optimized the design of permanent magnet type transverse flux linear motors (TFLM) to reduce the weight of motor with constraints of thrust and detent force using RSM and genetic algorithms (GA). RSM is well adapted to make analytical model of motor weight with constraints of thrust and detent forces. It enables objective function to be easily created and a great computational time to be saved. Finite element computations are used for numerical experiments on geometrical design
variables in order to determine the coefficients of a second-order analytical model for the RSM. GA is used as a searching tool for design optimization.

Hasanien (2011) repeated the above design optimization problem using RSM and particle swarm optimization (PSO). PSO is a computational intelligence-based technique that is not largely affected by the size and nonlinearity of the problem and can converge to the optimal solution in many problems where most analytical methods fail to converge. The effectiveness of the proposed PSO model is then compared with that of the conventional optimization models and genetic algorithms model. With this proposed PSO technique, the weight of the initially designed TFLM and its detent force can be reduced, as well as its thrust force can be increased.

Hasanien & Muyeen (2012) attempted to optimally design the parameters of the PI controllers used in the frequency converter of a variable speed wind turbine driven PMSG to achieve fault ride through as per the recent wind farm grid code. The setting of the parameters of the PI controller used in a large system is cumbersome, since it is difficult to express power system by a mathematical model or transfer function. The effectiveness of the designed parameters using GA-RSM is then compared with that obtained using a generalized reduced gradient (GRG) algorithm considering both symmetrical and unsymmetrical faults. The permanent fault condition due to unsuccessful reclosing of circuit breakers is considered as well. It represents another salient feature of this study. It is found that fault-ride-through of PMSG based WECS can be improved considerably using the parameters of its frequency converter obtained from GA-RSM.

Gaing et al (2014) presented a rigorous design of a brushless permanent-magnet motor with both lower cogging torque and higher efficiency, using response surface methodology with a quantum-behaved PSO (QPSO) operator for a portable electric power drill application. To decrease
noise and vibration of a slotted PM motor, cogging torque must be reduced. The 3-D finite element method (FEM) is employed as the tool for analyzing the cogging torque and performance of the proposed PM motor. The experimental results show that the proposed method can obtain the best combination of the geometric parameters for reducing the cogging torque and enhancing the operating efficiency.

1.4.4 Literature Survey on Multi-Objective Evolutionary Algorithm

The presence of multiple objectives in a problem, in principle, gives rise to a set of optimal solutions—Pareto-optimal solutions, instead of a single optimal solution. In the absence of any further information, one of these Pareto-optimal solutions cannot be said to be better than the other. This demands a user to find as many Pareto-optimal solutions as possible. Classical optimization methods (including the multi criterion decision-making methods) suggest converting the multi objective optimization problem to a single-objective optimization problem by emphasizing one particular Pareto-optimal solution at a time. When such a method is to be used for finding multiple solutions, it has to be applied many times, hopefully finding a different solution at each simulation run. Since evolutionary algorithms (EAs) work with a population of solutions, a simple EA can be extended to maintain a diverse set of solutions.

Srinivas & Deb (1995) proposed a non-dominated sorting genetic algorithm (NSGA) which is one of the first such EAs. With an emphasis for moving toward the true Pareto-optimal region, an EA can be used to find multiple Pareto-optimal solutions in one single simulation run.

Over the past decade, a number of multi-objective evolutionary algorithms (MOEA) have been suggested (Deb 2001, Fonseca & Fleming 1993, Horn et al 1994, Srinivas & Deb 1995 and Zitzler & Thiele 1998). The
primary reason for this is their ability to find multiple Pareto-optimal solutions in single simulation run. These algorithms demonstrated the necessary additional operators for converting a simple EA to a MOEA. Two common features on all three operators were the following: i) assigning fitness to population members based on non dominated sorting and ii) preserving diversity among solutions of the same non dominated front. Particularly, the interest has been to introduce elitism to enhance the convergence properties of a MOEA.

Among the existing elitist MOEAs, Zitzler and Thiele’s SPEA (Zitzler & Thiele 1998), Knowles and Corne’s Pareto-archived PAES (Knowles & Corne 1999) and Rudolph’s elitist GA (Rudolph 1999) are well studied and presented in this thesis.

Zitzler & Thiele (1998) suggested an elitist multi-criterion EA with the concept of non domination in their strength-Pareto EA (SPEA). They suggested maintaining an external population at every generation storing all non dominated solutions discovered so far beginning from the initial population. This external population participates in all genetic operations. At each generation, a combined population with the external and the current populations is first constructed. All non dominated solutions in the combined population are assigned a fitness based on the number of solutions they dominate and dominated solutions are assigned fitness worse than the worst fitness of any non dominated solution. This assignment of fitness makes sure that the search is directed toward the non dominated solutions. A deterministic clustering technique is used to ensure diversity among non dominated solutions.

Knowles & Corne (1999) suggested a simple MOEA using a single-parent single-offspring EA similar to (1+1)-evolution strategy. Instead of using real parameters, binary strings were used and bitwise mutations are
employed to create offspring. In their Pareto-archived evolution strategy (PAES), with one parent and one offspring, the offspring is compared with respect to the parent. If the offspring dominates the parent, the offspring is accepted as the next parent and the iteration continues. On the other hand, if the parent dominates the offspring, the offspring is discarded and a new mutated solution (a new offspring) is found.

However, if the offspring and the parent do not dominate each other, the choice between the offspring and the parent is made by comparing them with an archive of best solutions found so far. The offspring is compared with the archive to check if it dominates any member of the archive. If it does, the offspring is accepted as the new parent and all the dominated solutions are eliminated from the archive. If the offspring does not dominate any member of the archive, both parent and offspring are checked for their nearness with the solutions of the archive. If the offspring resides in a least crowded region in the objective space among the members of the archive, it is accepted as a parent and a copy of added to the archive. Crowding is maintained by dividing the entire research space deterministically in $d^m$ subspaces, where $d$ is the depth parameter and $m$ is the number of decision variables, and by updating the subspaces dynamically.

Rudolph (1999) suggested, but did not simulate, a simple elitist MOEA based on a systematic comparison of individuals from parent and offspring populations. The non dominated solutions of the offspring population are compared with that of parent solutions to form an overall non-dominated set of solutions, which becomes the parent population of the next iteration. If the size of this set is not greater than the desired population size, other individuals from the offspring population are included. With this strategy, the convergence of this algorithm to the Pareto-optimal front is proved. Although this is an important achievement in its own right, the
algorithm lacks motivation for the second task of maintaining diversity of Pareto-optimal solutions. An explicit diversity-preserving mechanism must be added to make it more practical.

Zitzler et al (2000) showed that elitism helps in achieving better convergence in MOEAs.

Over the years, the main criticisms of the NSGA approach have been as follows.

1) High computational complexity of non dominated sorting: The currently-used non dominated sorting algorithm has a computational complexity of $O(MN^3)$ (where $M$ is the number of objectives and $N$ is the population size). This makes NSGA computationally expensive for large population sizes. This large complexity arises because of the complexity involved in the non dominated sorting procedure in every generation.

2) Lack of elitism: Results of references Zitzler et al (2000) and Rudolph (1999) show that elitism can speed up the performance of the GA significantly, which also can help preventing the loss of good solutions once they are found.

3) Need for specifying the sharing parameter: Traditional mechanisms of ensuring diversity in a population so as to get a wide variety of equivalent solutions have relied mostly on the concept of sharing. The main problem with sharing is that it requires the specification of a sharing parameter ($\sigma_{share}$). Though there has been some work on dynamic sizing of the sharing parameter, a parameter-less diversity-preservation mechanism is desirable.
Deb et al (2002) presented a non dominated sorting-based multi objective EA, called non dominated sorting genetic algorithm II (NSGA-II), which alleviates all the above three difficulties. Specifically, a fast non-dominated sorting approach with computational complexity is presented. Also, a selection operator is presented that creates a mating pool by combining the parent and offspring populations and selecting the best (with respect to fitness and spread) solutions. Simulation results on difficult test problems show that the proposed NSGA-II, in most problems, is able to find much better spread of solutions and better convergence near the true Pareto-optimal front compared to Pareto-archived evolution strategy and strength-Pareto EA—two other elitist MOEAs that pay special attention to creating a diverse Pareto-optimal front. On a problem having strong parameter interactions, NSGA-II has been able to come closer to the true front than the other two approaches.

Pombo et al (2014) proposed a genetic evolutionary algorithm NSGA-II for the optimization between the maximal return of investments on existing assets, while maintaining the quality of service provided. The trade off between total cost of investments and service quality levels SAIDI (System Average Interruption Duration Index) and SAIFI (System Average Interruption Frequency Index) is analyzed, to choose the optimal placement of switches in the distribution electrical networks. The proposed method was tested with a Portuguese real distribution network. The obtained results proved the performance of the adopted approach.

1.5 OBJECTIVE OF THE THESIS

Huang et al (2012) analyzed the stability of wind turbine with direct drive permanent magnet synchronous generator by effectively designing the controllers’ parameters. However, proper tuning method is not
followed to obtain desired response and parameter variations are not addressed in coordinated manner.

Liteteratures, described in section 1.4.2, ignore the need for coordinated operation of machine side and grid side converter controllers. Due to the stochastic nature of wind speed, generator speed varies continuously to track the maximum power point. These speed variations are translated into generator output power variations and in turn into DC link voltage fluctuations. So it needs a coordinated control action.

Uehara (2011) and Li et al (2012) considered the coordinated control action between machine side and grid side converters. Hence there arises a need for coordinated tuning of MSC and GSC controllers. Coordinated tuning of these controllers using the traditional trial and error method is a cumbersome and challenging task. Therefore optimization techniques are being utilized for the coordinated tuning of controllers.

Lopes et al (2010) presented GA based tuning of proportional-integral (PI) controllers gains for the grid-side converter of direct-drive synchronous wind generator. However, tuning of machine side converter is not addressed and GA based tuning of controller parameters is time consuming.

Rodrigues et al (2013) proposed a multi-objective genetic algorithm (MOGA) to fine-tune the proportional and integral (PI) gains of the both machine and grid side converter control structure. But a proper objective function i.e, relationship between output and control variables is not used in optimization problem and most importantly controller parameters are not tuned for time domain study.
Response surface methodology (RSM) is applied in this thesis to design optimization problem aimed at reducing the cost of expensive analysis methods (e.g. finite element method) and their associated numerical noise. The problem can be approximated with smooth functions to relate output and input variables that improve the convergence of the optimization process because they reduce the effects of noise and they allow for the use of derivative-based algorithms.

From the literature survey, the following main objectives are arrived.

- To design MSC and GSC controllers of PMSG based WECS in a co-ordinated manner by posing it as a optimization problem and solving it using GA and RSM - NSGA II.
- To analyze the impact of MSC and GSC controllers' parameters on small signal stability of power system.
- To analyze the impact of penetration of different combinations of Type-1, Type-2 and Type-4 wind turbines based wind farms on small signal stability of multi machine power system.
- To analyze the impact of Type-1 and Type-2 wind turbines based wind farms on small signal stability of 156 bus Indian utility grid system.

1.6 ORGANIZATION OF THE THESIS

The thesis is organized into six chapters including this chapter.

Chapter 1 starts with introduction to Indian wind scenario. A detailed literature survey on SCIG based FSWECS, WRIG based...
PVSWECS and PMSG based VSWECS is presented. Need of coordinated (tuning) design of MSC and GSC controllers of PMSG based VSWECS is presented. Further, a detailed literature survey on RSM and multi-objective evolutionary algorithms is also presented.

Chapter 2 presents small signal model of the synchronous generators, fixed speed WECS, partial and full variable speed WECS, network and load. The assumptions involved in arriving at the small signal model are delineated in Chapter 2.

Chapter 3 presents an optimum design procedure for the coordinated tuning of MSC and GSC controllers of PMSG based WECS. The MSC and GSC controller parameters are determined by three different approaches. Three approaches are posed as optimization problems with the objective functions- (1) Maximization of the overall system damping (2) Minimization of time domain performance indices and (3) Simultaneously optimizing both 1 and 2 (multi-objective problem).

The system damping is obtained through eigenvalue analysis and performance indices are obtained from transient stability analysis of the test system. The first two single objective optimization problems (approaches 1 and 2) are solved by using genetic algorithm whereas the multi-objective optimization problem (approach 3) is solved by the proposed RSM-NSGA II technique.

The proposed approaches are tested on a SMIB system with PMSG based WECS and results are compared. Transient stability analysis of SMIB system is performed with tuned controller parameters obtained by solving the above said optimization problems. The analysis is conducted for step change in wind velocity, variable wind speed under partial load operation, variable wind speed near rated speed, a load change and a fault.
In Chapter 4, analysis carried out in Chapter 3 is extended to a multi-machine system. By providing PMSG based VSWECS at different locations, coordinated tuning is performed by using the above 3 approaches. A three-machine-nine-bus system (Anderson & Fouad 1978) is considered for analysis.

The effects of location and penetration of fixed speed, partially variable speed and variable speed wind farm on stability of the test system are investigated. With optimized controller parameters, small signal stability analysis is performed against step change in wind velocity, change in wind turbines and a load change and verified with time domain analysis.

Chapter 6 deals with small signal stability analysis of a 156-bus Indian Utility system that consists of 10 synchronous generators and 40 fixed speed wind farms. Eigenvalues are analyzed for different wind velocities and it is validated with time-domain analysis. Finally, a study is made on this system by replacing the some fixed speed wind farms by Type-2 wind farms that employ rotor resistance control. Time domain analysis is also performed against step change in wind velocity and three phase fault and compared with 156 bus system with only FSWFs.

In Chapter 7 the main contributions in the thesis are presented and scope for further work is highlighted.