CHAPTER 1

INTRODUCTION

1.1 WIND ENERGY

Among the various renewable energy sources, wind energy conversion systems have been found to be viable in contributing significant amounts of electric power, when installed in locations where adequate wind potential is available. Solar photo voltaic systems give DC power directly from sunlight, but from the cost consideration, they are restricted to small power applications, at least till the commercialization of cheaper photo voltaic cells.

Today, wind turbine deployment shows the fastest growth both nationally and globally. Wind Electric Generators (WEG) were earlier used for isolated power supplies especially in remote locations and rural areas. In recent times, grid-connected wind electricity generation shows the highest rate of growth, achieving global annual growth rates in the order of 20-28%. According to World Wind Energy report 2010, published by World Wind Energy Association, Germany, worldwide installed capacity of wind energy reached 196630 MW out of which 37642 MW were added in 2010.

Thanks to the combination of domestic policy support for wind power and conductive environment created by utilities, India has become the country with the fifth largest installed wind power capacity in the world. The penetration level of wind energy is increasing day by day.
1.2 COMPONENTS OF WEG

A wind turbine (WT) is a rotating machine which converts the kinetic energy of wind into mechanical energy. If the mechanical energy is then converted to electricity, the combined unit is called a WEG. In a common WEG, the wind pushes the turbine blades, which turns the shaft. The shaft spins the rotor of the generator and electromagnetism in the generator produces electricity. Figure 1.1 shows the components of WEG. Modern WEGs normally have the following components (Bibek Samantaray 2010):

**The rotor:** Large WTs consist of two or three rotor blades which rotate around a horizontal hub. The hub is connected to a gear box and generator, which are located inside the nacelle, that is mounted on the top of the tower. The shape of the turbine blade is designed such that when air crosses it, an aerodynamic lift is produced and the rotor to which it is attached turns.

![Figure 1.1 Components of Wind Electric Generator](image)
The nacelle: The rotor is linked by a shaft directly to the nacelle, which contains the drive shaft, gearbox, high speed shaft, generator and controlling equipment. In order to ensure that a low speed of the turbine produces a high rotational speed of the generator, a gear box is inserted in the transmission system. It has been found that for a particular site, one particular choice of the gear ratio gives the highest system efficiency. WEGs deal with these huge variations in power using several aerodynamic strategies that regulate the power captured by the rotor.

The tower: The tower is used to increase the height of the turbine systems so that the higher wind speeds are captured. Tower supports the nacelle and the rotor. The electricity produced by the generator comes down the cables inside the tower and passes through a transformer into the electricity network.

The brake: In the event of load tripping or accidental disconnection of electrical load, the rotor speed may increase dangerously. This may even lead to the mechanical destruction of the rotor. Moreover, at very high wind speeds, the electrical power output has to be kept within the limits to protect the generator and the power electronic accessories. In these situations, it is advisable to use brakes. Either an eddy current or a mechanical brake or a combination of these is installed in most WTs. The mechanical brake is necessary for stalling these turbines in gusty winds.

1.3 SQUIRREL CAGE INDUCTION GENERATOR

The WEGs use different types of generators such as squirrel cage induction generator, wound rotor induction generator, doubly fed induction generator and permanent magnet synchronous generator (Soens 2004).
Squirrel Cage Induction Generator (SCIG) is the most used generator type for WEGs. Induction generators are the same as induction motors in construction. Generator operation occurs only for speeds higher than the synchronous speed. Below the synchronous speed, the machine operates as a motor. The generator is connected directly to the three-phase grid without power electronic interface, except for protection devices and optionally a soft-starter, that has to limit inrush currents during start-up. The supply voltage is dictated by the grid and is not normally controlled. A severe grid voltage dip may yield a decrease of torque and may cause instability. Induction generators are simple and durable machines that allow only small variations in rotor speed, the slip being in the range of 1-3%. Higher values of slip correspond to faster rotor speeds and more generated power. As this speed range is so small, machines using SCIG are typically called as fixed speed WEGs. Figure 1.2 shows the schematic diagram of SCIG connected to the grid.

Figure 1.2  Schematic diagram of Fixed speed WEG using SCIG connected to the grid
The advantages of SCIG are:

(i) well-known and robust technology, high efficiency, easy and relatively cheap because of mass production of the generator.

(ii) no use of slip rings and brushes, and therefore it is maintenance-free.

The drawbacks of this generator are

(i) the speed varies only over a narrow range, having certain implications such as:

(a) Wind speed fluctuations are directly translated into electromechanical torque variations, rather than rotational speed variations. This causes high mechanical and fatigue stresses on the system and may result in swing oscillations between turbine and generator shaft. Also the periodical dips in torque due to tower effect and shear effect are not damped by speed variations, which may result in higher flicker values.

(b) The turbine speed cannot be adjusted to the wind speed to optimize the aerodynamic efficiency. As it is known from the basic WT theory, the highest fraction of kinetic energy that a turbine can extract from the air is 59% (the Betz limit). The actual value of this fraction, called the performance coefficient $C_p$, depends on the turbine design and on the ratio between the turbine tip speed and wind speed. For every wind speed, there
exists one turbine speed resulting in the highest \( Cp \).
This optimal speed cannot be continuously achieved with the SCIG.

(iii) A gearbox in the drive train is required as the generator speed and turbine speed are different.

(iv) The machine always consumes reactive power and its value cannot be controlled. There is a fixed relation between its reactive and active power. This makes it impossible to support grid voltage control.

(v) Its power factor is also low mainly at low load conditions.

1.4 PROBLEMS FACED BY GRID CONNECTED WIND ELECTRIC GENERATORS

1.4.1 Voltage Stability Issues

Like conventional power plants, wind power plants must provide the power quality required to ensure the stability and reliability of the power system to which it is connected. Power quality is defined as “any occurrence manifested in voltage, current or frequency deviation that results in damage, upset, failure or malfunction of end use equipment”. So, it is very important to understand the sources of disturbances that affect the power quality of the grid. WTs tend to create voltage problems on weak power system. As a result of wind variability, weak grids with high wind penetration may experience significant voltage swings. Most grid codes require that the grid voltage remain within 10% of nominal value for proper operation. A traditional switched capacitor bank used in wind farm for reactive power compensation cannot easily follow voltage swings, since these devices are only designed to correct slowly-changing voltages that naturally occur in load cycles over 24 hours.
1.4.2 Harmonics

WTs use variable speed generation technologies to increase the energy captured at different wind speeds. In most of the cases, the variable speed operation is attained by the use of power electronic converters, which introduce harmonics into the grid and cause many power quality problems in the power system.

1.4.3 Fault Tolerance

Fault protection is carefully designed and built in all parts of the electrical grid. Fault usually causes a decrease in system voltage due to high currents involved. After a short delay, most traditional power plants in the region will automatically increase their reactive power output and help in raising the voltage. It is crucial to keep post fault voltages close to nominal to ensure that protection systems operate properly and to prevent blackouts. Wind turbines do not operate like traditional power plants during a fault. Manufacturers want to protect their equipment so that they often programme the turbines simply to disconnect from the grid during any electrical disturbance. As the number of large wind farms continue to grow, if a fault suddenly send all turbines offline in a wind farm, the combined effect of fault and a sudden loss of generation might cause severely decreased voltages and lead to voltage instability. In response to this concern, transmission operators and international regulating agencies such as Federal Energy Regulatory Commission (FERC) have drafted proposals that new wind turbines be equipped with Low Voltage Ride Through (LVRT) capability (Sarasij Das 2009). This new regulation has presented a challenge for many turbine manufacturers, especially manufacturers of Doubly Fed Induction Generator (DFIG) turbines. Due to the nature of the generator, a sudden drop in voltage at the machine stator terminals causes large currents to flow in the rotor. These currents can easily exceed the inverter ratings and damage the rotor
inverter. To protect the rotor inverter, most DFIG turbine manufacturers include a mechanism where upon over-current, the inverter is disconnected from the rotor, and a short circuit or a group of resistors is connected to the rotor instead. This effectively turns the DFIG into a SCIG or Wound Rotor Induction Generator (WRIG), which starts consuming reactive power. This could decrease voltages further and do more harm than the wind turbine getting simply disconnected from the grid.

![Figure 1.3 LVRT capability requirement of Wind Electric Generators](image)

**Figure 1.3 LVRT capability requirement of Wind Electric Generators**

Figure 1.3 shows the LVRT capability requirement of WEGs, one of the several conditions in the grid codes (Florin lov 2007) introduced by various countries. It demands the WEG to remain connected to power network during severe grid faults for 625ms, which should be the transient stability margin of WEG. With increasing penetration, wind farms will have major impact on Indian power system. The Fault Ride Through (FRT) or LVRT requirements in Indian Wind Grid Code (IWGC) resembles to that of the international practice. Normally wind farms connected below 66kV are smaller in size. The requirement of FRT can affect the economics of smaller wind farms in the present scenario. However it may be advised that FRT capability be provided for future wind farm development with due consideration to cost impact (Sarasij Das 2009). Wind farms using SCIG directly connected to the network would be disconnected from the power
system when the grid voltage drops more than 30% below the rated value as the reactive power demand by SCIG during grid faults is not met by capacitor banks installed at SCIG terminals. It is important to study the dynamic performance of grid connected WEG because its performance is affected by disturbances in the grid such as frequency variations, voltage sag, swell and especially the faults.

A power quality survey was undertaken at the 110kV/11kV Andhiyur substation in Tamilnadu, for examining the cause for tripping of WEGs (Thirumoorthy 2009). Voltage dips and other electrical data were collected simultaneously at 110kV level, 11kV level and at a single WEG terminal. Results are shown in Table 1.1.

**Table 1.1 WEG tripping due to voltage sag in the feeder**

<table>
<thead>
<tr>
<th>Date</th>
<th>No. of WEGs tripping</th>
<th>Percentage of voltage dip recorded</th>
<th>Cause for the voltage dip</th>
</tr>
</thead>
<tbody>
<tr>
<td>19-5-08</td>
<td>10</td>
<td>15.8</td>
<td>Tripping of adjacent feeder due to earth fault</td>
</tr>
<tr>
<td>21-5-08</td>
<td>28</td>
<td>52</td>
<td></td>
</tr>
<tr>
<td>22-5-08</td>
<td>6</td>
<td>25.6</td>
<td></td>
</tr>
</tbody>
</table>

From the data, it could be inferred that severe dip in voltage has caused tripping of WEGs. The dips in the feeder are caused by tripping of adjacent feeder connected to the same substation. The fault in the feeder caused its tripping. During the voltage dip, feeder current rose abnormally creating severe strain on the WEGs and connected transformers. Frequent strain may ultimately damage the generator and transformer. To overcome these issues, it was recommended to install improved version of relays in the feeder breaker so that the fault clearing time is minimized or otherwise prolonged fault condition would be injurious to the wind electrical system.
1.5 LITERATURE REVIEW

A literature survey was carried out on the various works done to improve the quality of power with the help of SuperCapacitor Energy Storage (SCES) system and on the application of STATic synchronous COMpensator (STATCOM) in windfarm to have the grid compliance. Finally, the use of STATCOM with supercapacitor for various applications were also studied and explained briefly.

Kazimierczuk et al (1996) did the feasibility study on application of SCES in aircraft distributed power systems for improving voltage regulation and providing emergency power to loads as per military standards.

Halpin et al (1996) proved that the static condenser consisting of a DC energy storage element, AC to DC converter and a DC to AC converter is used to mitigate the voltage sag and voltage swell by implementing it in a distribution feeder of 14.8kV supplying a load of 300kW. This system supplied power for 1sec when there was a complete failure of the distribution feeder.

Saad-Saoud et al (1998) described a comprehensive study of the application of a STATCOM to a wind farm. Several strategies for steady-state voltage and reactive power flow control of a wind farm equipped with a STATCOM were investigated. The unity power flow strategy for controlling reactive power flows of a wind farm was found to have minimal losses in real distribution networks.

Miller (1999), Belhachemi et al (2000) and Yao et al (2006) dealt with the supercapacitor modeling and parameters determination by different methods such as voltage drop method, constant current charging method, self-discharge method and electrochemical impedance spectroscopy. Based on the
construction of the supercapacitors, they were represented by a complex RC network with nonlinear capacitance.

Adrian et al (2000) presented basic supercapacitor technology, component specific properties as well as state of the art product applications such as maintenance free power sources for IC memories and microcomputers, load levelling in electric and hybrid vehicles, starting of engines, toy, GSM and SAM applications etc.

Domenico Casadei et al (2002) suggested the use of the bank of supercapacitors and DC-DC boost converter as the power conditioning system with a three-phase Voltage Source Inverter (VSI) so that the stored energy could be used to compensate the flicker phenomena due to switching-on and off of the load.

Rufer et al (2002) did the simulation and implemented SCES system to improve voltage profile of elevators. SCES based system was also developed for voltage drop compensation in weak distribution systems such as trolley buses by Rufer et al (2004).

Chai Chompoo-inwai et al (2004) discussed the reactive power compensation techniques of the induction generator based wind generation. Their voltage ride-through capabilities during system disturbances with two possible reactive compensation techniques, fixed capacitor and Static VAR Compensator (SVC) were studied and compared.

Divya et al (2004) gave the idea of using a simple model for grid connected induction generators while studying the dynamic behaviour of such systems. It introduced the concept of critical clearing slip and the capabilities of the proposed model had been illustrated by studying the behaviour of a
sample system for the common types of events such as mechanical, electrical and switching disturbances.

Belyakov (2005) showed that Electrochemical capacitor sets could work as online short duration UPS upto one minute, solving transient problems in case of line overloads, short time fluctuations of current, voltage and frequency.

Sharmeela et al (2005) implemented three level voltage source converter based D-STATCOM to reduce the voltage sag and swell in a 11kV distribution feeder by compensating the fluctuations in reactive power.

Belyakov (2006) suggested that Electrochemical double layer capacitors with carbon/carbon electrodes and aqueous electrolyte are best suitable for high power applications because of many advantages.

Han Chong et al (2006) proved that cascaded multilevel inverter based STATCOM with supercapacitor could be used in power system dynamic voltage management specifically with the windfarm fluctuations and electric arc furnace flicker mitigation.

Active and reactive power compensation based on SCES in electric power distribution system to improve power supply reliability and quality had been suggested by Rong Lu et al (2006).

Arun Karuppaswamy (2007) emphasized that STATCOM can be used as a solution to power quality issues in the distribution system. It used the synchronous reference frame strategy to generate current reference for compensation equipment.

Molinas et al (2007) presented an overview of STATCOM for voltage quality problems related to fluctuating wind power fed to power
network. Simulation and experimental results for stationary, dynamic and transient modes of operation with emphasis on LVRT operation were described in this paper.

It had been shown in the simulation by Chad Abbey et al (2007) that the performance of DFIG based wind generator integrated with super capacitor had the ability to smoothen out the fast wind induced power variations. It was also shown that it provided an effective means to ride through disturbances and exhibits superior characteristics, during and following extreme voltage events.

Jin Geun Shon et al (2007) explored the use of DC/DC converter with the double-layer capacitor as dynamic compensator of voltage sag.

Philippe Maibach et al (2007) dealt with the application of medium voltage STATCOM technology in wind parks by ABB to meet the new grid code requirements. Static and dynamic reactive power supply, voltage control and harmonics in wind farm were analyzed by performing on-site measurements with STATCOM in Scotland.

Molina et al (2008) examined the use of Distribution - STATCOM (D-STATCOM) integrated with a supercapcitor through a buck-boost converter to have power quality improvement in a distribution system. Simulation was done for a 1.2kV, 50Hz distribution system supplying a load of 1.5MW, 0.35MVar. Supercapacitor of 6F, 1170V was used in the work.

Srithorn et al (2008) suggested that super capacitor with a DC-DC converter and its proper control could help STATCOM deliver both real and reactive power instantaneously into grid, which is the key for improving and enhancing the transient stability of the power system.
Zhengping Xi et al (2008) explored the application of STATCOM with super capacitor to mitigate the problems of DC voltage dip, and overcurrent trips of STATCOM. Simulation results in MATLAB Simulink showed that the proposed system enhanced the power quality and improved distribution system reliability under single line to ground fault, line to line fault and three phase faults.

Parkhideh et al (2008) introduced D-STATCOM with supercapacitor to enhance voltage regulation of transmission and distribution system. The performance improvements were verified by conducting simulation on rapidly varying arc furnace loads whose fluctuating real power was supplied by D-STATCOM with supercapacitor system.

Kanabar et al (2008) provided the analytical formulae for critical slip and critical clearing time to obtain the rotor stability margin of fixed speed WEG. He proved that the rotor stability margin of WEG was enhanced with the help of additional reactive power compensation devices. Also, steady state analysis had been carried out to calculate the exact amount of additional reactive power required to satisfy LVRT requirements.

Aditya Jayam Prabhakar (2008) investigated the use of STATCOM with wind farms for stabilizing the grid voltage at Point of Common Coupling(PCC) after grid side disturbances such as three phase to ground fault, sudden load changes etc.

Byung et al (2008) proposed a new configuration of Unified Power Quality Conditioner (UPQC) with DC-DC converter and supercapacitor for compensating voltage interruption, reactive power, harmonic current, voltage sag and swell, voltage unbalance with simulation in PSCAD/EMTDC. The
results were verified through experimental works with prototype for non linear load and sensitive load.

Baran et al (2008) proposed STATCOM with battery energy storage system for smoothing intermittent power output of a large windfarm and compensating fast voltage fluctuations at the interconnecting bus with simulations in PSCAD/EMTDC.

Deswal et al (2009) proved experimentally that SCES could be used to provide ride through capability of Adjustable Speed Drives (ASD) by compensating voltage sags for short voltage interruptions.

Virulkar et al (2009) suggested the use of Flexible AC Transmission System (FACTS) to solve the voltage flicker problems in sawmill by rapidly controlling the active and reactive power.

Sverre (2009) presented a detailed model comprising of STATCOM, half bridge buck-boost DC converter and SCES System for grid voltage stabilization in wind farms. Simulations were done in PSCAD which showed that the proposed system was capable of reactive power compensation apart from compensating instantaneous active power fluctuations of wind farms.

Camm et al (2009) provided the basic guidelines for the application of reactive power compensation systems to be used as part of a wind power plant. Brief history of wind power plant reactive power compensation system and how to size the compensation system are discussed in this paper.

Thakare et al (2009) recommended fuzzy controller based STATCOM to stabilize the grid connected squirrel cage wind generator system during voltage sags and swells in the grid network.

Huan-ping et al (2009) analysed the dynamic performance of wind farm during faults and the effect of FRT with SVC was studied. The performance of Fixed Speed Induction Generator (FSIG) with and without SVC were compared in the simulation. They proved that SVC can improve static and dynamic stability of power system.

Hendri Masdi et al (2009) presented the construction of a prototype D-STATCOM for voltage sag mitigation in balanced distribution system along with simulation in PSCAD/EMTDC.

Ghazi et al (2010) investigated the stability improvement of a grid connected fixed speed wind farm following grid faults using braking resistors along with reactive power compensating devices.

Alam et al (2010) investigated the potential of SCES system with STATCOM for enhancing FRT capability of FSIG for symmetrical three phase fault. Simulation results showed that WEG regains prefault condition immediately after the fault is cleared.

Mohod et al (2010) examined the power quality problems due to installation of WEGs with the grid. In the proposed scheme, STATCOM with battery energy storage system helps to mitigate reactive power demand and fluctuating real power of induction generator.

Le et al (2010) discussed about the ride-through capability of a large induction-generator based wind park with different reactive power
support solutions. This paper prioritized the usage of STATCOM, SVC or switched capacitor banks in different grid conditions.

Sureshkumar et al (2010) proved that STATCOM is used to mitigate flicker level and harmonics produced by grid connected wind turbine fed induction generator and synchronous generator using PSCAD.

Khadem et al (2010) presented a technical overview of power quality problems associated with renewable based distributed generation system and how custom power devices such as STATCOM, Dynamic Voltage Restorer(DVR) and UPQC with battery energy storage and braking resistor could play an important role in improving power quality and stability of windfarm.

Gong Wenming et al (2011) presented the general explanation of the induction generator’s response to voltage dips, examined the application of several devices for enhancing its LVRT capability and also provided clues of the development of further LVRT research at the level of windfarms.

Rahim et al (2011) demonstrated that STATCOM with DC-DC converter and supercapacitor can be used for achieving significant low voltage withstand capability of wind generation systems having induction generator by simulation. Decoupled P-Q control of STATCOM is implemented for re-establishing terminal voltage following a disturbance on the system.

1.6 OBJECTIVES OF THE PRESENT STUDY

From the review of literature, it is seen that the supercapacitor energy storage system is used for many power quality applications. Also it is noted that in certain SCIG based windfarm, STATCOM is used for reactive power compensation (Philippe Maibach 2007). If a supercapacitor is added to
the STATCOM through a DC-DC converter, the real power fluctuations in the windfarm can be compensated to some extent. There is a necessity for the windfarm operators to meet the grid code requirements regarding FRT capability, harmonics, voltage fluctuations etc. for interconnecting their WEGs to the grid. In order to improve voltage recovery at the terminals of the induction generator and to increase its critical clearing time, reactive power injection method is useful. Thus the primary aim of this thesis has been set as to assess the performance of a grid connected WEG that uses dynamic reactive power compensation, namely STATCOM with supercapacitor. The following are the specific objectives of the present research work:

1. To develop a computer simulation model of grid-connected WEG comprising wind turbine driven SCIG using MATLAB Simulink as the simulation tool.

2. To simulate different reactive power compensation techniques such as (i) Fixed Capacitance(FC) Compensation (ii) STATCOM Compensation and (iii) STATCOM with Supercapacitor compensation, and to analyze the effects of each on the performance of the WEG under different load conditions of the grid.

3. To simulate various grid fault conditions and study the FRT or LVRT capability of the grid-connected WT driven SCIG and assess the improvement when STATCOM with supercapacitor is added to the system; also, to examine voltage fluctuations, harmonics, reactive power consumption, power transients, DC link voltage dips and overshoots in STATCOM during the fault and settling time after the fault.
1.7 OUTLINE OF THE THESIS

The contents of the thesis are organized into seven chapters as follows:

**Chapter 1** deals with the various problems faced by grid connected WEG. It also gives a literature review on various works related to the application of STATCOM in windfarm and also the use of STATCOM with supercapacitor for various applications.

**Chapter 2** presents the development of a computer simulation of a WEG model comprising SCIG, WT and gear. Various parameters such as real and reactive power of SCIG and voltage at PCC are observed for different wind speeds with and without FC compensation. The performance under three phase to ground fault is observed for a particular wind speed.

**Chapter 3** focuses on the analysis of transient stability margin of SCIG with FC compensation at two different penetration levels during (i) single line to ground fault, (ii) double line to ground fault and (iii) three phase to ground fault.

**Chapter 4** gives the comparison of performance indices such as the maximum reactive power consumption of SCIG and maximum SCIG speed during fault for different fault conditions with FC compensation and STATCOM compensation. It also analyses the transient stability of SCIG with STATCOM compensation under different fault conditions. Simulation is done in MATLAB Simulink for (i) pure resistive load and (ii) resistive-inductive load each at (a) full load and (b) half load conditions. Vector control technique is implemented in STATCOM for generating pulses to the inverter.

**Chapter 5** presents a hardware laboratory study of the effect of wind speed changes on grid power quality parameters such as voltage,
frequency, power factor and harmonics at different penetration levels of grid-connected WEG. Wind power is simulated as the power output of the DC shunt motor. Linear and gust changes of wind speed are considered in the study beyond a constant value. It also focuses on the design, fabrication and testing of STATCOM for a laboratory prototype of 2.2 kW SCIG coupled with DC shunt motor to increase the LVRT capability of SCIG during the voltage sag in the grid. Control algorithm is implemented in PIC16F877a microcontroller.

Chapter 6 deals with the development of equivalent circuit model of 100PP14 supercapacitor by using charging and discharging tests. It also gives the simulation and analysis of transient performance of SCIG connected to STATCOM together with supercapacitor. Performance indices such as the transient stability margin of SCIG, maximum reactive power consumption of SCIG and maximum SCIG speed during fault, settling time after the fault and transients in STATCOM DC link capacitor voltage during fault, voltage fluctuations for random wind speed variations, voltage and current harmonics with and without the supercapacitor are observed and examined.

Chapter 7 summarizes the conclusions and contributions of the work and provides some suggestions for future work.