CHAPTER 1
INTRODUCTION

1.1: Background of wind energy

Windmills have been used for at least 3000 years, mainly for grinding grain or pumping water, while in sailing ships the wind has been an essential source of power for even longer. From as early as the thirteenth century, horizontal-axis windmills were an integral part of the rural economy and only fell into disuse with the advent of cheap fossil-fuelled engines and then the spread of rural electrification. To use wind energy efficiently and to concentrate the visual impact of modern wind turbines, the regions with a good wind climate, a tendency to group turbines in wind farms can be observed. These wind farms are connected to high voltage transmission grids and thus directly influence the dynamic behavior of the electrical power system [1].

Modern electricity-generating wind turbines now use three-bladed upwind rotors although two-bladed, and even one-bladed, rotors were used in earlier commercial turbines. Reducing the number of blades means that the rotor has to operate at a higher rotational speed in order to extract the wind energy from wind turbine. Initially these turbines were small, sometimes rated at only 30 kW, but were developed over the next 15 years to around 40-m diameter, 800–1,000 kW. However, by the mid-1990s it was becoming clear that for larger wind turbines it would be necessary to move away from this simple architecture and to use a number of the advanced concepts (e.g. variable-speed operation, pitch regulation, advanced materials) that had been investigated in the earlier research work. Large wind turbines are up to 100 m in diameter, rated at 3 to 4 MW are used. Most of the largest wind turbines now being installed operate at variable-speed, as the power electronic converters also allow much greater control of the output power and it is easier to comply with the requirements of the power system network operator [2].

In the past, wind power plants were with smaller sizes and usually in the range of tens of megawatts per wind farm. With the increase of the turbine capacity and the number of turbines connected to the grid at the substation, the wind farm capacity
reached to hundreds of megawatts. Increased level of integration of wind energy converters to grid and its impact on grid are of great concerns to researcher and utilities. Study of impact of integration of large scale wind farms on grid stability, voltage quality and grid disturbances on operation of wind turbine is important to provide cost effective solutions. Maintaining voltage and frequency ride-through requirements is essential by providing adequate voltage support and dynamic reactive power compensation. Wind turbines have to sustain voltage sags during grid faults by increasing reactive power compensation. The low voltage ride through (LVRT) or faults ride-through (FRT) is defined as the ability of wind energy converter to remain connected during faults on power system [3].

A growing power demand coupled with depleting natural resources has led to an increased need for energy production from renewable energy sources. The latest technological advancements in wind energy conversion and an increased support from governmental and private institutions have led to increased wind power generation in recent years. Wind power is the fastest growing renewable source of electrical energy. Total wind power installation in the World is 2,82,482 MW. Table1.1 and 1.2 indicates the global wind power capacity & Indian wind power capacity respectively. India ranks 5th globally and Maharashtra state ranks 3rd regarding wind power installation [4].

Table 1.1: Global wind power capacity [4]

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<tr>
<th></th>
<th>China</th>
<th>United States</th>
<th>Germany</th>
<th>Spain</th>
<th>India</th>
<th>U. K.</th>
<th>Italy</th>
<th>France</th>
<th>Canada</th>
<th>Portugal</th>
<th>Rest of World</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global wind power capacity = 282482 MW</td>
<td>75564</td>
<td>60007</td>
<td>31332</td>
<td>22796</td>
<td>19051</td>
<td>8445</td>
<td>8144</td>
<td>7196</td>
<td>6200</td>
<td>4525</td>
<td>39852</td>
</tr>
</tbody>
</table>

Table 1.2: Indian wind power capacity [4]

<table>
<thead>
<tr>
<th></th>
<th>T.N</th>
<th>Gujarat</th>
<th>Maharashtra</th>
<th>Karnataka</th>
<th>Rajasthan</th>
<th>M.P</th>
<th>A.P</th>
<th>Kerala</th>
<th>Orissa</th>
<th>W.B</th>
<th>Rest of India</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind power capacity in India = 19051 MW</td>
<td>7154</td>
<td>3093</td>
<td>2976</td>
<td>2113</td>
<td>2355</td>
<td>386</td>
<td>435</td>
<td>35.1</td>
<td>2</td>
<td>1.1</td>
<td>3.2</td>
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</table>
The wind power penetration has increased drastically in the past few years; hence it has become necessary to address problems associated with stability of power system. During a large disturbance, such as a grid fault, the wind turbines gets disconnected from the power network and reconnect when normal operation has been resumed as long as wind power penetration remains low. However, the penetration of wind power is increasing rapidly and will influence overall power system behavior. Moreover, due to growing demands and limited resources, the power industry is facing challenges on the electricity infrastructure. As a consequence, it will become necessary to maintain continuous operation of wind turbine during grid disturbances.

In the era of a deregulated electricity industry, the policy of open access to transmission systems, which helped to create competitive electricity markets, led to a huge increase in energy transactions over the grid and possible congestion in transmission systems. The expansion of power transfer capability of transmission systems has been a major problem over the past two decades. Under these conditions, the modern power system has to confront some major operating problems, such as voltage regulation, power flow control, transient stability, and damping of power oscillations, etc. [5].

Flexible AC transmission system (FACTS) devices can be a solution to these problems. They are able to provide rapid active and reactive power compensations to power systems, and therefore can be used to provide voltage support and power flow control, better transient stability and improve power oscillation damping. Suitably located FACTS devices allow more efficient utilization of existing transmission networks. Among the FACTS family, the shunt FACTS devices such as the static synchronous compensator (STATCOM) has been widely used to provide smooth and rapid steady state and transient voltage control at points in the network [6].

A wind farm is usually spread over a wide area and has many wind generators, which produce different amounts of power as they are exposed to different wind patterns. Power control is vital for transient and voltage stability during faults and is required to meet the connection requirements of the wind turbines to the grid which vary mostly with the short circuit capacity of the system. Additional reactive power compensation is required to meet reactive power demand of the generator and the
matching transformers during fault condition to avoid voltage collapse. Low voltage ride through (LVRT) system is a recently introduced requirement that transmission operators demand from wind farms. A STATCOM is being evaluated for its performance to effectively provide LVRT for wind turbines in a wind farm. This thesis explores the possibility of enabling wind farms to provide voltage support during normal conditions, as well as under conditions when system voltages are not within desired limits. The transient behavior of wind farms can be improved by injecting large amounts of reactive power during fault. This thesis examines the use of STATCOM in wind farms to stabilize the grid voltage after grid disturbances such as severe system faults.

The wind turbines (WTs) considered in this thesis are singly fed induction generator (SFIG) or squirrel cage induction generator (SCIG), doubly/double fed induction generator (DFIG) or wound rotor induction generator (WRIG) also electrically excited synchronous generator (EESG). In this thesis, a combined case study of interconnected three types of wind energy converter with STATCOM and with linear & nonlinear load connected to grid is carried out to study impact of mentioned factors and provide cost effective solution.

1.2: Wind turbine concepts and generator types

To understand the wind energy, it is important to learn wind turbines. Wind turbines can be categorized according to the axis of rotation: vertical and horizontal axis. The only vertical axis machine that has had success is the Darrieus rotor; named after its inventor the French engineer G.M. Darrieus, who first developed the turbines in the 1920s as shown in figure 1.1. The vertical wind turbines are suitable for low power applications. The advantage of the vertical wind turbines is that the generator and transformer can be placed on the ground near the rotor blades. This results in low installation and maintenance cost. It absorbs wind from all direction. It does not need yaw control mechanism. Tower required is light in weight. Blades are spin around are almost always in pure tension, so it is light in weight & inexpensive. Disadvantages of vertical axis wind turbine (VAWT) are that blades are closed to ground where wind speed is low. Wind near the surface of earth is not only slower but also more turbulent
which increases stresses on VAWT. At low speeds, it has a very little starting torque and high speed, output power cannot be controlled as pitch control is not provided. The power efficiency is limited to 25% [7].
Most popular type of wind turbine is horizontal axis wind turbines (HAWT) as shown in figure 1.2. Similar to the vertical wind turbines, the horizontal wind turbines can be built with two or three blades. Wind turbines have control system that controls the speed of rotor blades. The anemometer measures the wind speed and transmits the data to the controller. The pitch angle of the rotor blades is controlled by the controller to attain the maximum wind power and to limit the mechanical power in case of the strong wind. The rotor blades are pitched to decrease the angle of attack from the wind when the rated power is reached. The yaw drive can turn the wind turbine compartment or so called nacelle according to the direction of the wind measured by the wind vane [8].

In addition to the pitch control, the maximum power from the wind can be limited by passive stall control for small and medium-size wind turbines. The stall control avoids the rotation of the blades. Contrarily to the pitch-angle control, passive stall control has fixed pitch-angle rotor blades. The passive stall control relates to the design of the rotor blades that leads to turbulence or so called stall on the back of the blades to reduce the power extracted from the wind. As the capacity of wind turbines increases, active stall control is used for large wind turbines, with rating above 1 MW. The active stall control is similar to the pitch-angle control. The rotor blades are rotated to obtain the maximum power extract. When the extracted power reaches the rated power, opposite to the pitch-angle control, the active stall control turns the rotor blades to increase the angle of attack from the wind to provoke the turbulence. Disadvantages of HAWT are that tower shadow effect exists because every time a blade swings behind the tower, it encounters a brief period of reduced wind which causes the blade to flex. It increases blade noise [9].

The development of modern wind power conversion technology has been going on since 1970s, and the rapid development has been seen from 1990s. Various wind turbine concepts have been developed and different wind generators have been built. Referring to the rotation speed, wind turbine concepts can be classified into fixed speed, limited variable speed concept with a partial-scale power converter and variable speed concept with a full-scale power converter.
There are different types of generators, which are in use by the wind turbines to generate electricity. These generators can be classified by different aspects such as with respect to speed i.e. constant speed or variable speed, with respect to working principle i.e. with or without a power electronic converter. Figure 1.3 shows classification of generators.

Three types of typical generator systems for large wind turbines exist. The first type is a constant speed or fixed-speed wind turbine system using a multi-stage gearbox and a standard squirrel-cage or singly fed induction generator (SCIG), directly connected to the grid. The second type is a variable speed wind turbine system with a multi-stage gearbox and a doubly fed induction generator (DFIG), where the power is fed to grid from stator as well as rotor. The third type is also a variable speed wind turbine, but it is a gearless wind turbine system with a direct-drive generator, normally a low-speed high-torque synchronous generator and a full-scale power electronic converter are used [9].

1.2.1: Fixed (Constant) speed concept

This configuration is known as the singly fed induction generator concept (SFIG concept). The fixed speed wind generator systems have been used with a multiple-stage gearbox and a SCIG directly connected to the grid through a
transformer as shown in figure1.4. The SCIG operates only in a narrow range around the synchronous speed. The wind turbine equipped with this type of generator is often called the fixed-speed wind generator system. This is the conventional concept applied by many Danish wind turbine manufacturers during the 1980s and 1990s, i.e. an upwind, stall-regulated, three-bladed wind turbine concept using an SCIG, referred as ‘Danish concept’. SCIG always draws reactive power from the grid.

The excitation to induction generator is provided to the stator windings and the grid frequency decides the synchronous speed of rotation. Speed of the rotating magnetic field in the stator depends on the number of poles and applied frequency and if the rotor of induction machine is rotated with the speed higher than the synchronous speed, then electric power is supplied to the grid by the induction machine. A gearbox with a high ratio is provided between the wind turbine and the rotor to raise the speed of the rotor in order to operate induction machine as generator. Both active and reactive power of the induction machines are functions of slip. The slip can be defined as the difference between the synchronous speed ($W_s$) and rotor speed ($W_r$).

Mathematically slip can be expressed as:

$$S = \frac{W_s - W_r}{W_s} \times 100\% \quad (1.1)$$
When the slip is negative, the induction machine supplies the active power and operates as a generator. When the slip is positive, the induction machine consumes the active power and it operates as a motor. Reactive power is consumed at both positive and negative slip operation.

The well-known advantages of SCIG are it is robust, easy and relatively cheap for mass production. In addition, it enables stall-regulated machines to operate at a constant speed when it is connected to a large grid, which provides a stable control frequency. Although the stall control method is usually used in combination with the fixed speed SCIG for power control, the active stall control or pitch control have also been applied.

Disadvantages of SCIG for the fixed speed wind turbine concept are as follows:

- The speed is not controllable and variable only over a very narrow range. The fixed speed concept means that wind speed fluctuations are directly translated into electromechanical torque variations, this causes high mechanical and fatigue stresses on the system (turbine blades, gearbox and generator) and may result in swing oscillations between turbine and generator shaft. The periodical torque dips because of the tower shadow and shear effect are not damped by speed variations and result in higher flicker. Furthermore, the turbine speed cannot be adjusted with the wind speed to optimize the aerodynamic efficiency. Although a pole-changeable SCIG has been used in some commercial wind turbines, it does not provide continuous speed variations.

- A three-stage gearbox in the drive train is necessary for this wind turbine concept. Gearboxes represent a large mass in the nacelle, and also a large fraction of the investment costs.

- It is necessary to obtain the excitation current from the stator terminal of SCIG. This makes it impossible to support grid voltage control.

- The induction generator is excited by the grid and consumes reactive power; hence the power factor is less than one and cannot be controlled.

- The speed cannot be controlled either [9].
1.2.2: Limited variable speed concept with a partial-scale power converter

This configuration is known as the doubly fed induction generator concept (DFIG concept), which corresponds to a variable speed wind turbine with a WRIG and a partial-scale power converter on the rotor circuit, as shown in figure 1.5. The induction machine used for power generation is of a wound type construction. It has two windings, one in the stator and one in the rotor (squirrel cage rotor has copper bars instead of windings on it). The stator windings are connected directly to the network. The rotor windings are also connected to the grid via a frequency converter by means of slip rings. When the stator is excited, a rotating magnetic field is produced. The speed of the rotating magnetic field depends on the system frequency and the number of poles. The mechanical power captured from the wind is converted into electrical power. This electrical power is fed into the grid by both stator and rotor windings. Since the power in the rotor circuit is at a different frequency, which differs from the network frequency and is a function of generator slip. The output from rotor circuit is first converted into a DC quantity and again converted into an AC quantity with grid frequency. A gearbox is provided between the rotor and the generator to adopt the speed of the induction generator.

The stator is directly connected to the grid, whereas the rotor is connected through a power electronic converter. The power converter controls the rotor frequency and thus the rotor speed. This concept supports a wide speed range operation, depending on the size of the frequency converter. Typically, the variable speed range is $\pm 30\%$ around the synchronous speed. The rating of the power electronic converter is only 25 to 30% of the generator capacity, which makes this concept attractive and popular from an economic point of view.

DFIG system has the following disadvantages:

- A multi-stage gearbox is still necessary in the drive train because the speed range for DFIG is far from a common turbine speed of 10 to 25 rpm. A gearbox is inevitable to have some drawbacks, such as heat dissipation from friction, regular maintenance and audible noise.
The slip ring is used to transfer the rotor power by means of a partial-scale converter, which requires a regular maintenance, and may be result in machine failures and electrical losses.

Under grid fault conditions, on the one hand, large stator currents result in large rotor currents, so that the power electronic converter needs to be protected from destruction; on the other hand, large stator peak currents may cause high torque loads on the drive train of wind turbines.

According to grid connection requirements for wind turbines, in case of grid disturbances, a ride-through capability of DFIG is also required, so that the corresponding control strategies may be complicated [9].

1.2.3: Variable speed direct-drive concept with a full-scale power converter

This configuration is known as the electrically excited synchronous generator concept (EESG concept). The EESG is usually built with a rotor carrying the field system provided with a DC excitation. The stator carries a three-phase winding quite similar to that of the induction machine. The rotor may have salient poles or may be cylindrical. Salient poles are more usual in low-speed machines and may be the most useful version for application to direct-drive wind turbines. A grid connection scheme of EESG for direct-drive wind turbines is shown in figure 1.6. The amplitude and
frequency of the voltage can be fully controlled by the power electronic at the generator side, so that the generator speed is fully controllable over a wide range, even at low speeds. In addition, the EESG has the opportunities of controlling the flux for a minimized loss in different power ranges, because the excitation current can be controlled by means of the power converter in the rotor side. Moreover, it does not require the use of permanent magnets (PMs), which would represent a large fraction of the generator costs, and might suffer from performance loss in harsh atmospheric conditions. Therefore it is the mostly used direct-drive generator type in the current market.

Disadvantages of direct-drive EESG systems can be summarized as follows:

- In order to arrange space for excitation windings and pole shoes, the pole pitch has to be large enough for the large diameter-specific design, so a larger number of parts and windings probably make it a heavy weight and expensive solution.
- It is necessary to excite the rotor winding with DC, using slip rings and brushes, or brushless exciter, employing a rotating rectifier and the field losses are inevitable [9].
1.3: Wind energy generating system

Figure 1.7 presents the topology of a complete wind energy conversion system (WECS).

![Diagram of WECS topology]

WECS produce electricity by using the power of wind to drive an electrical generator. The conversion of the kinetic energy of the incoming air stream into the electrical energy takes place in two steps: the extraction device, i.e., the wind turbine rotor captures the wind power movement by means of aerodynamically designed blades, and converts it into rotating mechanical energy, which drives the generator rotor. The electrical generator then converts this rotating mechanical power into electrical power. A gear box may be used to match the rotational speed of the wind turbine rotor with one that is appropriate for the generator. The electrical power is then transferred to the grid through a transformer. Power electronics converters can also be used for enhanced power extraction and variable speed operation of the wind turbine as shown in figure 1.8.
It is optional to tie the low speed shaft of the rotor blades to the high speed shaft of the generator with a gear box. In some cases, gearboxes are undesirable because they are expensive, bulky, and heavy. A multi-pole generator is an alternative way of a gearless system. The configurations of wind turbines and the grid interconnection depend on the type of generators [10].

The power cable transmits the electrical power to a transformer. The transformer steps up the low voltages of the generator to the distribution or sub-transmission level of the connected system. The voltages from the generator are typically in a few hundred volts. The maximum output voltage of the wind turbines is 690 Volts.
Wind turbines extract the energy from the wind by transferring the thrusting force of the air passing through the turbine rotor into the rotor blades. The rotor blades are aerofoil that acts similarly to an aircraft wing; this is the so-called principle of lift. This can be seen in the cross-section of a rotor wing as shown in figure 1.9.

As an effect of the resulting air flow, the windward side of the aerodynamic profile is over-pressured while the leeward side is under-pressured. This differential pressure creates a thrust force. This lifting force is perpendicular to the direction of the resulting force (resulting wind speed) reacted by the flowing wind towards the turbine wing and the local rotational speed of the wing. As a result, the lifting force is converted into a mechanical torque. The torque makes the shaft, as part of the turbine rotor, turn. The power in the shaft can be used with integrated generators, convert the shaft power into electricity [11].

Kinetic energy of air of mass \( m \) moving at speed \( V \) so kinetic energy, (K.E.) is given by:

\[
\text{K. E.} = \frac{1}{2} mV^2
\]  

(1.2)

Mass in motion carries a certain amount of energy. This kinetic energy varies in proportion to the product of the mass and the square of the velocity. In units of time, this energy is similar to the power.

\[
P_{\text{wind}} = \frac{1}{2} mV^2
\]  

(1.3)

Mass of air per second \( m = \rho AV \)  

(1.4)

However, not all the power can be extracted by the turbine and so a power coefficient (\( C_p \)) is defined. The power coefficient is simply the ratio of power extracted by the wind turbine rotor to the power available in the wind. \( P_w \) is the mechanical power of wind turbine in Nm/s. The power coefficient is given as 0.59. This coefficient is also known as Betz’s limit. This coefficient can be expressed as a function of tip speed ratio-\( \lambda \). If \( C_p - \lambda \) curve is known for specific wind turbine with a turbine rotor radius \( R \), it is easy to construct the curve of \( C_p \) against rotational speed for any wind speed [12].
In this study, a standard rotor with 3 blades is used. With a 3 or 2-blades wind turbine, the power coefficient will be smaller than its theoretical value. In the standard model of wind turbine available in the PSCAD master library, the power coefficient is defined with the following formula from PM Anderson model. (PSCAD manual) [13].

Cp is maximum at $\beta = 0$

$$\gamma = 2.237 \frac{\text{Wind speed}}{\text{Hub speed}}$$  \hspace{1cm} (1.5)

Power co-efficient Cp from PM Anderson model can be calculated for $\beta=0$ as

$$Cp = 0.5(\gamma - 0.022\beta^2 - 5.6)e^{-0.17\gamma}$$  \hspace{1cm} (1.6)

Wind turbine power output $P_{wt} = Cp \frac{1}{2} \rho AV^3$  \hspace{1cm} (1.7)

1.4: Wind turbine control systems

Wind turbines require certain control systems. Horizontal-axis turbines have to be oriented to face the wind. In high winds, it is desirable to reduce the drive train loads and protect the generator and the power electronic equipment for overloading, by limiting the turbine power to the rated value up to the furling speed. At gust speeds, the machine has to be stalled. At low and moderate wind speeds, the aim should be to capture power as efficiently as possible. Along with many operating characteristics, the technical data sheet of a turbine mentions its output at a particular wind speed. This is the minimum wind speed at which the turbine produces its designated output power. For most of the turbines, this speed is normally between 9 and 16 m/s. The choice of the rated wind speed depends on the factors related to the wind characteristics of a given site. The generator rating is best chosen so as to best utilize the mechanical output of the turbine at the rated wind speed.

With the development of power converter technologies, several different types of wind turbine configurations, using a wide variety of electric generators, are available. Major difference among WECS concepts is the electrical design and control.
WECS can be classified according to the speed control ability, leading to WECS classes differentiated by generator speed, according to the power control ability, leading to WECS classes differentiated by the method employed for limiting the aerodynamic efficiency above rated power. Input wind power control ability divides WECS into three categories: stall-controlled, pitch-controlled, and active-pitch controlled. Power control ability refers to the aerodynamic performance of wind turbines. There are different ways to control aerodynamic forces on the turbine rotor and thus to limit the power in very high winds in order to avoid the damage to the wind turbine [14].

Wind turbines can have four different types of control mechanisms, as discussed below:

**1.4.1: Pitch angle control**

The system changes the pitch angle of the blades according to the variation of wind speed. With pitch control, it is possible to achieve a high efficiency by continuously aligning the blade in the direction of the relative wind. On a pitch controlled machine, as the wind speed exceeds its rated speed, the blades are gradually turned about the longitudinal axis and out of the wind to increase the pitch angle. This reduces the aerodynamic efficiency of the rotor, and the rotor output power decreases. When the wind speed exceeds the safe limit for the system, the pitch angle is so changed that the power output reduces to zero and the machine shifts to the stall mode. After the gust passes, the pitch angle is reset to the normal position and the turbine is restarted. At normal wind speeds, the blade pitch angle should ideally settle to a value at which the output power equals the rated power.

The input variable to the pitch controller is the error signal arising from the difference between the output electrical power and the reference power. The pitch controller operates the blade actuator to alter the pitch angle. During operation below the rated speed, the control system endeavours to pitch the blade at an angle that maximizes the rotor efficiency. The generator must be able to absorb the mechanical power output and deliver to the load. Hence, the generator output power needs to be simultaneously adjusted [15].
1.4.2: Stall control

- **Passive stall control:** Generally, stall control to limit the power output at high winds is applied to constant-pitch turbines driving induction generators connected to the network. The rotor speed is fixed by the network, allowing only 1 to 4% variations. As the wind speed increases, the angle of attack also increases for a blade running at a near constant speed. Beyond a particular angle of attack, the lift force decreases, causing the rotor efficiency to drop. This lift force can be further reduced to restrict the power output at high winds by properly shaping the rotor blade profile to create turbulence on the rotor blade side not facing the wind [15].

- **Active stall control:** In this method of control, at high wind speeds, the blade is rotated by a few degrees in the direction opposite to that in a pitch controlled machine. This increases the angle of attack, which can be controlled to keep the output power at its rated value at all high wind speeds below the furling speed. A passive controlled machine shows a drop in power at high winds. The action of active stall control is sometimes called deep stall. Owing to economic reasons, active pitch control is generally used only with high-capacity machines [15].

1.4.3: Yaw control

Turbine is continuously oriented along the direction of the wind flow. This is achieved with a tail-vane in small turbines, using motorized control systems activated either by fan-tail, in case of wind farms, by a centralized instrument for the detection of the wind direction. It is also possible to achieve yaw control without any additional mechanism, simply by mounting the turbine downwind so that the thrust force automatically pushes the turbine in the direction of the wind. Speed of the rotor can also be controlled using the yaw control mechanism. The rotor is made to face away from the wind direction at high wind speeds, thereby reducing the mechanical power.
Yawing often produces loud noise, and it is restriction of the yawing rate in large machines to reduce noise is required [15].

1.4.4: Power electronic control

In a system incorporating a power electronic interface between the generator and load (or the grid), the electrical power delivered by the generated to the load can be dynamically controlled. The instantaneous difference between mechanical power and electrical power changes the rotor speed following the equation:

\[
\begin{align*}
J \frac{d\omega}{dt} &= \frac{P_m - P_e}{\omega} \\
\end{align*}
\]  

(1.8)

Where \( J \) is the polar moment of inertia of the rotor, \( \omega \) is the angular speed of the rotor, \( P_m \) is the mechanical power produced by the turbine, and \( P_e \) is the electrical power delivered to the load.

\[
\frac{1}{2} J (\omega_2^2 - \omega_1^2) = \int_{t_1}^{t_2} (P_m - P_e) \, dt
\]  

(1.9)

Advantages of power electronic control:

- Smooth in operation
- No mechanical action is involved

Disadvantage of power electronic control:

- Fast variation of speed requires a large difference between the input power and output power, which scales as the moment of inertia of the rotor resulting in a large torque and hence increased stress on the blades.
- Continuous control of rotor speed implies continuous fluctuation of the power output to the grid, which is usually undesirable for the power system [15].
1.5: Control Strategy

Wind turbines generate power by converting the kinetic energy of air into rotating mechanical power. The design of wind turbines is governed by the need to withstand mechanical loads. Most wind power sites experience high wind speeds only during a few hours per year and some form of power regulation is necessary if a design is to be economical. The aerodynamic design can be regulated either by designing the blades to go into an aerodynamic stall above a certain wind speed or by designing the blades as feathered in order to spill the unwanted power. The first method is called stall-regulation; the second method is called pitch-control. One advantage of stall-regulation is the simplified mechanical design which allows the blades to be attached rigidly to the hub. In addition, stall-regulation will not permit power excursions from gusty winds to pass through the drive train. The disadvantages are the technical difficulties of aerodynamic stall design, the need for a rotor brake, motor driven start and more aerodynamic noise.

Figure 1.10 shows a design of wind speed-power curve which reflects maximum power point tracker (MPPT) operation mode and blade pitch control operation mode. At low wind speeds, the generated power is too low to be exploited. Normally, wind turbines are started when the wind speed exceeds 3 to 4 m/s. This wind speed is denoted as the cut-in wind speed. Cut-in wind speed is the lowest wind speed at which wind turbine starts to generate power [16].

![Power curve of a wind turbine](image)

Figure 1.10: Power curve of a wind turbine [16]
As can be seen in figure 1.10, a wind turbine is started at cut-in wind speed and the power increases with the cube of the wind speed until the rated wind speed is reached. Rated wind speed is the wind speed at which the wind turbine generates the rated power, which is usually the maximum power wind turbine can produce. At wind speeds from 12 m/s to 25 m/s the power is limited to the rated power of the wind turbine by means of stall-regulation or pitch-control. At wind speeds over 20 to 25 m/s wind turbines are normally stopped to avoid high mechanical loads. The wind speed at which wind turbines are stopped is called the cut-out wind speed. Cut-out wind speed is the wind speed at which the turbine ceases power generation and is shut down to protect the turbine from mechanical damage [16].

1.6: Technical challenges

Most of the wind turbines are located in remote locations due to high wind speeds and away from the load centers where the grid is weak. This weak grids experience various disturbances like frequent faults, unbalance voltages and voltage variations. Till now the penetration level of the wind energy was low and thus disconnection of the turbine during these disturbance conditions didn’t impact power system operation. As more and more electricity is being generated from wind, disconnection of turbine during disturbances will impact the power system operation and even the post disturbance condition leading to under-utilization of wind turbine. Thus during disturbances like fault condition, unbalance voltages and variations in the grid voltage are a real challenge. The location and intermittent nature of wind turbine machines can cause power quality problems. Wind turbines, especially inductive machines, tend to absorb reactive power from the system and produce a low power factor. If wind turbines absorb too much reactive power, the system can become unstable [17].

The challenges associated with operation of a wind farm lead to a greater concern for the operation under disturbances within the nearby power system. Asymmetric and symmetric faults can lead to voltage instabilities. However, tripping of the generators due to under voltage and over speed of the generators can result in
voltage stability problems and even small disturbances may lead to widespread tripping and associated instabilities [18].

As the penetration of wind increases, the way in which it interacts with the power system becomes increasingly important. However, for high penetrations, requirements are likely unreasonable and in some cases may even be detrimental to the stability of the system. For instance, without voltage regulation controls, the voltage may often fluctuate outside the acceptable operating range and fast tripping of wind generators following under voltages have been shown to lead to voltage collapse, suggesting the need for low-voltage ride through capability. The problem of voltage regulation and reactive power control is even greater in the case of a weak connection. The large source impedance results in significant fluctuations in the voltage at the point of common coupling due to changes in power flows and in this case reactive compensation has been shown to be crucial. The ability to smooth the power oscillations will result in a more stable terminal voltage; however, reactive compensation would still be a strict requirement, in steady-state but even more importantly during transients [19].

Existing grid connection codes require fault ride-through (FRT) capabilities for wind turbines. Three-phase short-circuit faults are considered as the most challenging case among all. In most of the existing WECSs, the ability to ride through the grid faults is not possible without control or hardware modifications. The fault ride-through requirement, also named low-voltage ride-through (LVRT) requirement, imposes great challenges to wind turbine / converter manufacturers and designers [20].

Along with these issues, integration of wind turbine to grid faces few more challenges. They are:
1) Fluctuating nature of wind causes power variation and thus the voltage oscillations
2) Preferred generators for wind turbine application are induction generator which draws large amount of reactive power for excitation purpose from grid and make the grid weak
3) Maintaining voltage at the connection point due to the weak grids, reactive power absorbed by the induction generators and varying wind power
4) The voltage of synchronous generator is variable due to variable wind and fluctuating voltage and power is a major concern in converter based grid connected system. This only increases the problem inherent to the power network and also makes the contribution difficult to manage and regulate the voltage and frequency
5) Power quality issues like voltage sag, voltage swell, interruption, under voltage, over voltage, harmonics, voltage unbalance, flicker
6) Low voltage ride through capability (LVRT)
7) Effect of short circuit ratio on operation of WEC and power quality of grid due to interconnection of wind farms
8) Effect of wind turbulence
9) Harmonic distortion due to integration of synchronous generators
10) Stability of wind turbine during grid disturbances

1.7: Aim of the thesis

Wind energy in India has an extremely bright future and there is no doubt that, in the renewable energy sector, wind power would play a predominant role in adding clean energy to the country’s grids. India has a huge potential of wind generation and every year many wind farms are being added and interfaced to grid. As compared to developed countries Indian grid is very weak with poor infrastructure. The percentage of wind-based generation will increase at faster rate, which will results into power quality, stability and reactive power management. So there is need to study effect of these factors to identify the main issues which are responsible for deterioration of power quality, reliability, security and stability of large wind farm grid as well as satisfactory operation of generator including ride through capability during normal as well as fault conditions.

Objective of the research work of this thesis are:

[1] Study and examine the main issues, which affects power quality, reliability, security and stability of large scale wind farm when it is connected to grid comprising of synchronous and induction generator by conducting actual measurements to identify reactive power, power quality problems, grid stability and security issues
including the ride through capability of both types of generator during normal grid and faulted grid conditions.


[3] Study of impact of wind generator (both types) on grid supply quality, reliability and security covering the effect of grid strength and type of connected load such as linear and nonlinear.

[4] Study of problems associated with wind farm comprising both types of generator from grid such as stability, reliability, quality and stability of wind turbines.

[5] Provide cost effective solutions for reactive power management, power quality issues, grid security and reliability issues including ride through enhancement of wind generator during normal and faulted conditions with modeling and simulation by PSCAD software.

1.8: Organization of thesis

This thesis is organized into eight chapters.

Chapter 1 covers introduction and classification of the wind turbine concepts & generator types. In this chapter various wind turbine concepts and different wind generators have been discussed. Three types of typical generator systems used in large scale wind farms are discussed. Different types of wind power control mechanisms are presented. Input wind power control ability divides wind energy conversion system (WECS) into four categories: pitch-controlled, stall-controlled, yaw control & power electronic controlled. Power control ability refers to the aerodynamic performance of wind turbines. There are different ways to control aerodynamic forces on the turbine rotor and thus to limit the power in very high winds in order to avoid the damage to the wind turbine. Control Strategy & technical challenges associated with wind farm, organization of thesis, contributions are covered.
Chapter 2 provides a literature review for modeling and control of the induction and synchronous generator-based WECS connected to power grid, steady state reactive power capability of the generator, power quality issues, low voltage ride through capability and grid code requirements for connecting wind turbines to power grid. Moreover, chapter 2 also presents the literature review for necessity of additional reactive power source in the generator-based wind turbine system. Modeling and control of the STATCOM is used to control the operation of induction and synchronous generator-based wind turbine system.

Chapter 3 provides problem identification and scope of work. Many researchers have focused on study of power quality, reactive power, stability, flicker, operation of wind energy generator under different grid conditions considering single type of generators. In large scale wind farms different types of generators are used with different wind farm topologies. More research was required to study all the issues mentioned and technical challenges of integration of large scale wind farms with different types of wind energy generator technologies with different topologies to provide cost effective optimal solutions.

Detailed scope of work covers study of power quality problems such as short duration RMS voltage variation (voltage sag, swell and interruption), long duration RMS voltage variation (under voltage & over voltage), voltage unbalance, flicker, harmonic distortion along with reactive power issues, low voltage ride through capability, fault ride through capability, effect of short circuit ratio, wind turbulence issues, voltage, power & rotor instability during fault related with integration of large scale wind farm with different generator technologies, different wind farm topologies are covered. Impact of factors responsible for deterioration of power quality of grid due to operation of different wind turbine generator technologies and impact of poor power quality of grid on wind turbine operational behavior, stability during all conditions of grid, wind farm topologies are covered in scope of work. Providing optimal cost effective solution to resolve technical issues related with integration of large scale wind farms with different types of wind generators, topologies under different conditions of grid are covered.
Chapter 4 describes the following four grid connected wind driven generator system description.

1) Grid connected wind driven squirrel cage (singly fed) induction generator system:

A wind farm typically consists of a large number of individual wind turbine generators (WTGs) with squirrel cage induction generators (SCIGs) connected by an internal electrical network. To study the impact of wind farms on the dynamics of the power system, an important issue is to develop appropriate wind farm models to represent the dynamics of many individual WTGs. The model is developed and compared by simulation & validation study in the PSCAD/EMTDC environment under different wind velocity and fluctuation conditions. Wind generators are primarily classified as fixed speed or variable speed. For the studies carried out in this chapter, it focuses on modeling the fixed speed unit. It consists of a 75 MW wind farm comprising 60 wind turbines, grouped into five clusters of similar properties. Each grouping contains 12 wind turbines of 1.25 MW unitary rating. The electric generators studied are squirrel cage machines of 1.6 MVA. The wind turbine designated has a stall regulated three-bladed horizontal axis rotor coupled to a squirrel cage induction generator. Each of these wind turbine units consists of rotor, gear box, squirrel cage induction generator and a 0.69/33 kV transformer. The large scale wind farm is connected to 33/132 kV substation to 220 kV, 200 MVA electric grid system is modeled by using PSCAD simulation software.

2) Grid connected wind driven doubly fed induction generator system:

The DFIG is wound rotor induction generator with the stator windings directly connected to the constant-frequency three-phase grid and the rotor windings is fed by the rotor side converter (RSC) and the grid side converter (GSC) connected back-to-back. At steady state the RSC independently regulates stator active and reactive powers whereas GSC keeps the DC link voltage constant independent of magnitude and direction of the rotor power. In this case the wind farm is represented using PSCAD library in PSCAD simulation software where one wind turbine and DFIG are represented as one equivalent DFIG driven by single equivalent wind turbine. The
wind turbine having capacity 0.8 MW designated has a stall regulated three-bladed horizontal axis rotor coupled to a wound rotor induction generator having capacity 1 MVA. The large wind farm is connected to 33/132 kV substation to 220 kV, 200 MVA electric grid system is modeled by using PSCAD simulation.

3) **Grid connected wind driven synchronous generator system:**

A wind farm typically consists of a large number of individual wind turbine generators (WTGs) with electrically excited synchronous generators (EESGs) connected by an internal electrical network. To study the impact of wind farms on the dynamics of the power system, an important issue is to develop appropriate wind farm models to represent the dynamics of many individual WTGs. The model is developed and compared by simulation studies in the PSCAD/EMTDC environment under different wind velocity and fluctuation conditions. Modeling of variable speed unit is carried out. It consists of a 75 MW wind farm comprising 45 wind turbines, grouped into five clusters of similar properties. Each grouping contains 9 wind turbines of 1.67 MW unitary rating. The electric generators are synchronous machines of 2 MVA. The wind turbine designated has a stall regulated three-bladed horizontal axis rotor coupled to a synchronous generator. The connection to the grid is then performed through a full AC/DC/AC converter. The main advantage of this strategy is to allow removing the gear box in the wind turbine. Each of these wind turbine units consists of rotor, synchronous generator and a 0.69/33 kV transformer. The large wind farm is connected to 33/132 kV substation to 220 kV, 200 MVA electric grid system is modeled by using PSCAD simulation.

4) **Large scale wind farm with combination of singly, doubly fed induction & synchronous generator system:**

A wind farm typically consists of a large number of individual wind turbine generators (WTGs) with squirrel cage induction generators (SCIGs), doubly fed induction generator and electrically excited synchronous generators connected by an internal electrical network. To study the impact of wind farms on the dynamics of the power system, an important issue is to develop appropriate wind farm models to
represent the dynamics of many individual WTGs. The model is developed and compared by simulation studies in the PSCAD/EMTDC environment under different wind velocities and fluctuation conditions. Modeling of the fixed speed unit & variable speed is carried out. Large scale wind farm having capacity of 150.8 MW consists of combination of all generators squirrel cage induction generators (SCIG), doubly fed induction generator (DFIG) and electrically excited synchronous generators (EESG).

In a 75 MW squirrel cage induction generator wind farm consists of 60 wind turbines, grouped into five clusters of similar properties. Each grouping contains 12 wind turbines of 1.25 MW unitary rating. The electric generators are squirrel cage machines of 1.6 MVA. The wind turbine designated has a stall regulated three-bladed horizontal axis rotor coupled to a squirrel cage induction generator. In a 0.8 MW wound rotor induction generator wind farm consists of 0.8 MW wind turbine machine designated has a stall regulated three-bladed horizontal axis rotor coupled to a wound rotor induction generator having capacity 1 MVA.

In a 75 MW synchronous generator wind farm comprising 45 wind turbines, grouped into five clusters of similar properties. Each grouping contains 9 wind turbines of 1.67 MW unitary rating. The electric generators are synchronous machines of 2 MVA. The wind turbine designated has a stall regulated three-bladed horizontal axis rotor coupled to a synchronous generator. The large wind farm is connected to 33/132 kV substation to 220 kV, 200 MVA electric grid system is modeled by using PSCAD simulation software.

Chapter 5 describes the comparison of SVC, STATCOM and UPFC is presented and based on technical merits, capabilities of various mentioned devices and requirements to resolve issues related with integration of large scale wind farms interface with grid, STATCOM device was considered for providing mitigation. Capacitor sizing criterion to provide reactive power by using STATCOM is discussed. Rating calculation and location of STATCOM for active, reactive, apparent power, dc link voltage, $V_{\text{cmax}}$, DC link capacitor rating is presented.
Chapter 6 provides the effect & mitigation techniques for following generator system:

1) Grid connected wind driven squirrel cage (singly fed) induction generator system:

In this chapter a wind turbine fed squirrel cage induction generator is modeled using PSCAD and different power quality issues like short duration variations (voltage sag, swell and interruption), long duration variation (under voltage, over voltage) harmonics for linear load & nonlinear load, voltage unbalance, flicker, reactive power issues, LVRT, effect of short circuit ratio, effect of wind turbulence & effect of voltage, power & rotor instability are analyzed. In this case study, wind farm with squirrel cage induction generator having capacity 75 MW is connected to 33/132 kV substation to 220 kV, 200 MVA electric grid system & STATCOM connected at PCC is modeled using PSCAD/EMTDC software.

The STATCOM used as a device to mitigate these problems and simulation results prove that STATCOM is an effective to mitigate these problems during continuous operation of grid connected wind turbines. Large scale wind farm consisting of squirrel cage induction generator connected by STATCOM is described in this chapter.

2) Grid connected wind driven doubly fed induction generator system:

Wind turbine fed doubly fed induction generator is modeled using PSCAD and different power quality issues like short duration variations (voltage sag, swell and interruption), long duration variation (under voltage, over voltage) harmonics for linear load & nonlinear load, voltage unbalance, flicker, reactive power issues, LVRT, effect of short circuit ratio, effect of turbulence & effect of voltage, power & rotor instability are analyzed. The STATCOM used as a device to mitigate these problems and simulation results prove that STATCOM is an effective to mitigate these problems during continuous operation of grid connected wind turbines. Analysis of large scale wind farm consisting of double fed induction generator with STATCOM is presented. In this case study, wind farm with doubly fed induction generator having capacity 0.8 MW is connected to 33/132 kV substation to 220 kV, 200 MVA electric grid system & STATCOM connected at PCC is modeled using PSCAD/EMTDC software. In this
case the wind farm is represented using PSCAD library in PSCAD simulation software where one wind turbine and DFIG are represented as one equivalent DFIG driven by single equivalent wind turbine. The wind turbine having capacity 0.8 MW designated has a stall regulated three-bladed horizontal axis rotor coupled to a wound rotor induction generator having capacity 1 MVA. Wind turbine units consists of rotor, gear box, wound rotor induction generator and a 0.69/33 kV transformer. The large wind farm is connected to 33/132 kV substation to 220 kV, 200 MVA electric grid system & STATCOM connected at PCC is modeled by using PSCAD simulation software.

3) Grid connected wind driven synchronous generator system:

In this chapter a wind turbine fed synchronous generator is modeled using PSCAD and different power quality issues like short duration variations (voltage sag, swell and interruption), long duration variation (under voltage, over voltage) harmonics for linear load & nonlinear load, voltage unbalance, flicker, reactive power issues, LVRT, effect of short circuit ratio, effect of turbulence & effect of voltage, power & rotor instability are analyzed. In this case study, wind farm with synchronous generator having capacity 75 MW is connected to 33/132 kV substation to 220 kV, 200 MVA electric grid system & STATCOM connected at PCC is modeled using PSCAD/EMTDC software.

The STATCOM used as a device to mitigate these problems and simulation results prove that STATCOM is an effective means to mitigate these problems during continuous operation of grid connected wind turbines. Large scale wind farm consisting of synchronous generator connected by STATCOM is described in this chapter.

4) Large scale wind farm with combination of squirrel cage, doubly fed induction & synchronous generator system:

In this chapter large scale wind farm having capacity of 150.8 MW consists of combination of all generators squirrel cage (SCIG), doubly fed induction (DFIG) and electrically excited synchronous generators (EESG). In a 75 MW squirrel cage
induction generator wind farm consists of 60 wind turbines, grouped into five clusters of similar properties. Each grouping contains 12 wind turbines of 1.25 MW unitary rating. The electric generators are squirrel cage machines of 1.6 MVA. The wind turbine designated has a stall regulated three-bladed horizontal axis rotor coupled to a squirrel cage induction generator. In a 0.8 MW wound rotor induction generator wind farm consists of 0.8 MW wind turbine machine designated has a stall regulated three-bladed horizontal axis rotor coupled to a wound rotor induction generator having capacity 1 MVA. In a 75 MW synchronous generator wind farm comprising 45 wind turbines, grouped into five clusters of similar properties. Each grouping contains 9 wind turbines of 1.67 MW unitary rating. The electric generators are synchronous machines of 2 MVA. The wind turbine designated has a stall regulated three-bladed horizontal axis rotor coupled to a synchronous generator. In this case study, large scale wind farm having capacity 150.8 MW is connected to 33/132 kV substation to 220 kV, 200 MVA electric grid system & STATCOM connected at PCC is modeled using PSCAD/EMTDC. Also power quality issues like short duration variations (voltage sag, swell and interruption), long duration variation (under voltage, over voltage) harmonics for linear load & nonlinear load, voltage unbalance, flicker, reactive power issues, LVRT, effect of short circuit ratio, effect of turbulence & effect of voltage, power & rotor instability are analyzed. The STATCOM is used to mitigate these issues and simulation results prove that STATCOM is an effective means to mitigate these problems.

Chapter 6 also gives the cost analysis of all generating system. A simulation model of large scale wind farm consisting of squirrel cage, double fed induction generator & synchronous generator system is designed in PSCAD software without STATCOM connected to the system having wind speed varying from 3 m/s to 30 m/s. Average power factor is calculated of the system by considering active power & apparent power. As induction generator requires reactive power for excitation purpose. Hence it lowers the power factor of the system. Status of power factor level & penalty (Monthly) without STATCOM connected to the system are evaluated.
Chapter 7 covers results, discussion and conclusion on the basis of simulation results of all cases considered in scope of work of this thesis. Simulation studies were carried out on following configuration of wind farms.

1) Singly fed induction generator wind farm having capacity of 75 MW comprising of sixty number of wind turbines

2) Doubly fed induction generator with 0.8 MW

3) Synchronous generator having capacity of 75 MW comprising of forty five number of wind turbines

4) Combination all three mentioned generator aggregated wind farm model with 150.8 MW capacity

Different studies carried out to study impact of grid side power quality disturbances on operational behavior of three types of wind energy generators.

a) Reactive power requirement, variations during different operating conditions of wind turbines and wind patterns, grid operating conditions under steady state and transient conditions.

b) Evaluation of low voltage fault ride through capability of three types of wind energy generators connected in different configuration for symmetrical and unsymmetrical power system faults.

c) Effect of short circuit ratio on operational behavior of different wind generators. Different parameters of generator studied are active, reactive power, voltage profile and generator speed.

d) Effect of various power system faults on voltage profile, active power, reactive power, rotor instability of three types of wind generators operating individually and in aggregated model.

e) Evaluation of low voltage fault ride through capability of different types of generators for seven types of voltage sags with different magnitude and duration, instantaneous, momentary and temporary voltage swell, under and over voltages with different magnitude and duration, Voltage unbalance.
Different studies are carried out to study impact of operation of wind turbine under different operating conditions on grid power quality as follows:

a) Effect of wind turbulence on wind speed with and without pitch angle control and its impact on power fluctuations.

b) Requirement of reactive power under different operating conditions of three types of generators.

c) Voltage and current harmonic distortion issues related with operation of three types of generators with linear and non-linear load.

d) Cost benefits analysis of reactive power compensation.

e) Effect of short circuit ratio on voltage harmonic distortion during operation of three types of wind energy generators used in aggregate model for linear and for different percentage of nonlinear as a part of total load.

f) Evaluation of current harmonic emissions at PCC with different short circuit ratios for aggregate wind model comprising of three types of wind energy generators.

Chapter 8 describes future scope work, bibliography & appendix

1.9: Contributions

The main contribution of this thesis is as follows:

1) Studied of all the issues related with integration of large scale wind farms to grid with different generators, wind farm topologies and all related factors which may govern power quality issues. Simulation of a large scale wind farm model includes a wind turbine with different types of generators, which are singly fed, doubly-fed induction and synchronous generator mainly used in large scale wind farms. All generators are connected in parallel at the point of common coupling (PCC) and connected to the utility grid through substation. Detailed simulation studies were carried out with these cases:

2) Evaluation of low voltage fault ride through capability of different types of generators for seven type of voltage sags A, B, C, D, E, F and G with different
magnitude and duration, instantaneous, momentary and temporary voltage swell, under voltage and over voltages with different magnitude and duration.

3) Effect of operation of singly fed, doubly fed induction and synchronous generators on current harmonic distortion at PCC with different short circuit ratios with linear and non-linear load connected to grid and comparison of current harmonic limits at PCC as per IEEE 519-1992 Standard.

4) Effect of grid side % voltage unbalance on operation of singly, doubly fed induction and synchronous generators.

5) Study of reactive power requirement in case of wind farm with singly fed induction generators, doubly fed induction generators, synchronous generators and wind farm with all three types of generators.

6) Effect of symmetrical and unsymmetrical grid faults on low voltage ride through capability of three different types of wind generators connected in different configurations.

7) Effect of short circuit ratio on operational behavior of different generators. Different parameters of generator studied are active, reactive power, voltage profile and generator speed.

8) Effect of wind turbulence on wind speed with and without pitch angle control and its effect on power fluctuations.

9) Effect of symmetrical and unsymmetrical grid faults on voltage profile, active, reactive power, rotor instability on three types of wind generators connection in wind form in different configurations.

10) Effect of operation of three types of wind generators on voltage flicker.

Based on the analysis of these studies, various issues related with interconnection of large scale wind turbines were identified and cost effective solution is provided for mitigation of power quality problems, reactive power, harmonic distortion, low voltage ride through capability by use of static synchronous
compensator (STATCOM). Simulation results were obtained with and without STATCOM.

The outcome of research work will be useful to Indian utilities, policy makers, regulators, wind energy farm developers, R & D bodies and various researchers.