CHAPTER 1

INTRODUCTION

1.1 MOTIVATION

In order to fulfill the increasing power demand, a lot of stress is imposed on conventional fossil fuel based power units. But a progressive exhaustion of fossil fuel based plants results in increasing global warming. It affects humans in several aspects i.e., economies, public health, environment, etc. The advent of renewable energy resources [1, 2] has resulted in promising solution to these problems. There are several renewable energy resources available for the electrical power system. Among those, wind energy [3, 4] is one of the rapidly growing renewable energy resources. One of the major benefits associated with wind power is that, after initial land and capital costs, there is essentially no cost associated with the production of power from wind energy conversion systems (WECS). First of all, wind energy resources are available in abundance both on land (onshore) and at sea (offshore). Moreover, wind farms are available in a wide range of sizes, and they normally occupy less land space per kWh of electricity generated than conventional power stations.

Wind turbines are quite tall which does not affect the use of the land for other purposes, i.e., agriculture, irrigation etc. Further, wind power investment cost is relatively lower compared to some of the other similar renewable resources like solar photovoltaic. Additionally, the environmental quality of wind turbines is high. Wind power generates enough electricity within around six months to compensate for all energy used during material extraction, turbine construction, installation, operation, with life-spans designed for approximately around twenty years [5]. Even though wind turbines have an effect on the landscape, which is not appreciated by everyone, the impact of wind turbines on nature and wildlife are small, particularly if wind turbines are sited well. In addition to that, the advantage of the wind
energy for the power system is not only its free and clean energy but also its high capacity. By aggregating multiple wind turbines as wind farm or park, greater amount of electrical power can be generated from it. To interconnect wind power to the utility grid, there must be an appropriate grid interconnection, control system and regulation to ensure high power quality, reliability and stability. However, the one of the most critical problems associated with wind power is that, the amount of power generated by the same is affected by the intermittent nature of wind flow and therefore become difficult to predict. Due to the variability of wind flow it is not always assured that, the scheduled power from WECS will match with the power available from wind energy. Therefore, in a wind integrated system, the nature of wind makes the above problem to be different in its modeling. It follows that, the grid integrated wind powered units, may introduce severe challenges to traditional generation scheduling methodologies and operation of power system. For satisfactory grid integration, the wind power fluctuation may have to be balanced by other types of generation. Alternatively, to compensate for the power imbalance due to uncertainty of wind, additional cost may have to be added with the total power generation cost of the system.

The intermittency of wind energy and a cost of affording the power imbalance due to the uncertainty, poses new generation scheduling challenges which need attention. An elaborated discussion related to the past research works in this field is given in subsequent sections of this chapter. These works motivated the present research to probe more into this area and to have a better understanding about the effect of wind power uncertainty on power system operation. Before, understanding the wind power generation and its fundamental constructional and operational issues, some data related to the global and Indian wind power generation scenario may be pertinent here.
1.2. GLOBAL AND INDIAN SCENARIO OF WIND POWER DEVELOPMENT

After a slowdown in 2013, the wind industry set a new record for annual installations in 2014. Globally, 51,473 MW of new wind generating capacity was added in 2014 [6] according to the global wind market statistics by the Global Wind Energy Council (GWEC)[7]. The figure represents a 44% increase in the annual market, and is a sure sign of the recovery of the industry after a rough patch in the past few years. Total cumulative worldwide installations stand at 369,597 MW at the end of 2014. Although a relatively newcomer to the wind industry compared with Denmark or the United States, India has the fifth largest installed wind power capacity in the world. By 31 March 2015, the installed capacity of wind power in India was 23,444 MW [7,8]. The gradual improvement of wind power installation in Indian power scenario from 2005-2014 is shown in Fig.1.1. It can be seen that the capacity of wind power installation during 2014 is more than that during 2013 by 2180 MW which depicts a significant advancement. Besides Indian power scenario, the global cumulative installed wind capacity from 1997-2014 is shown in Fig.1.2. It shows the consistent rise of wind potential due to its superiority over other similar resources. Top 10 cumulative wind power capacities till Dec 14 in global scenario is depicted in Fig.1.3. It reveals that India with 22465 MW installed capacity till Dec-14 contributes to 6.1% share in the global wind power capacity. Considerable improvement in the wind power installed capacity in Asia during 2014 as compared to worldwide scenario is shown by Fig.1.4. Before going for into detail modelling and the issues related to the integration of wind power to power system, a brief overview of the operations of conventional system is detailed in the next section.
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Fig. 1.1. Installed wind power capacity in India

Fig. 1.2. Global cumulative installed wind capacities 1997-2014.
<table>
<thead>
<tr>
<th>Country</th>
<th>MW</th>
<th>% Share</th>
</tr>
</thead>
<tbody>
<tr>
<td>PR China</td>
<td>114609</td>
<td>31.0</td>
</tr>
<tr>
<td>USA</td>
<td>65879</td>
<td>17.8</td>
</tr>
<tr>
<td>Germany</td>
<td>39165</td>
<td>10.6</td>
</tr>
<tr>
<td>Spain</td>
<td>22987</td>
<td>6.2</td>
</tr>
<tr>
<td>India</td>
<td>22465</td>
<td>6.1</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>12440</td>
<td>3.4</td>
</tr>
<tr>
<td>Canada</td>
<td>9694</td>
<td>2.6</td>
</tr>
<tr>
<td>France</td>
<td>9285</td>
<td>2.5</td>
</tr>
<tr>
<td>Italy</td>
<td>8663</td>
<td>2.3</td>
</tr>
<tr>
<td>Brazil</td>
<td>5939</td>
<td>1.6</td>
</tr>
<tr>
<td>Rest of the world</td>
<td>58473</td>
<td>15.8</td>
</tr>
<tr>
<td><strong>Total Top10</strong></td>
<td>311124</td>
<td><strong>84.2</strong></td>
</tr>
<tr>
<td><strong>World Total</strong></td>
<td>369597</td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

Fig.1.3. Top 10 cumulative wind power capacity till Dec 14 in global scenario.
Introduction

<table>
<thead>
<tr>
<th>Country</th>
<th>MW</th>
<th>% Share</th>
</tr>
</thead>
<tbody>
<tr>
<td>PR China</td>
<td>23196</td>
<td>45.1</td>
</tr>
<tr>
<td>Germany</td>
<td>5279</td>
<td>10.2</td>
</tr>
<tr>
<td>USA</td>
<td>4854</td>
<td>9.4</td>
</tr>
<tr>
<td>Brazil</td>
<td>2472</td>
<td>4.8</td>
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<td>India</td>
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<td>4.5</td>
</tr>
<tr>
<td>Canada</td>
<td>1871</td>
<td>3.6</td>
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<tr>
<td>United Kingdom</td>
<td>1736</td>
<td>3.4</td>
</tr>
<tr>
<td>Sweden</td>
<td>1050</td>
<td>2.0</td>
</tr>
<tr>
<td>France</td>
<td>1042</td>
<td>2.0</td>
</tr>
<tr>
<td>Turkey</td>
<td>804</td>
<td>1.6</td>
</tr>
<tr>
<td>Rest of the world</td>
<td>6854</td>
<td>13.3</td>
</tr>
<tr>
<td><strong>Total Top10</strong></td>
<td><strong>44620</strong></td>
<td><strong>87</strong></td>
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<tr>
<td><strong>World Total</strong></td>
<td><strong>51473</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

Fig. 1.4. Annual installed capacity by region 2006-14 as per GWEC

Fig. 1.5. Top 10 new installed capacity during Jan-Dec 2014 as per GWEC
1.3. OPERATION OF ELECTRIC POWER SYSTEM

The overall purpose of power systems is to supply electricity to consumers in a safe, reliable, and economic way. The primary structure of traditional power systems comprises of power generation, transmission and distribution to consumers, or loads. A so-called hierarchical structure is based upon a limited number of large, power plants delivering electricity to large loads spread over long geographical regions. Power flows from generation into high-voltage transmission networks and then into medium- and low-voltage distribution networks; in a top-down or vertical direction. The advantages of interconnected and vertically integrated power systems include economies of scale in power generation, increased reliability, a reduced reserve margin and aggregation of load variations.

In observing the primary structure of power systems, it is important to note that electrical energy has not been possible to be stored in significant amounts. Electrical power is consumed at the same moment it is generated. For a reliable power supply it is therefore essential to maintain a precise balance between power demand and generation. In principle, it is possible to maintain the power balance by adjusting both generation and demand. However, conventionally the central generation units follow the demand at all times. The operation of power systems is therefore critically dependent on the capabilities of generators in balancing the load. Power generation in traditional power systems is based on primary energy sources in the form of fossil fuels or water. Small numbers of large-scale central generation units based on primary energy sources are capable of providing power balance in the entire power system. Therefore, system loads can vary within a framework of predicted load during the day throughout the year, with the help of some reserve generation. However, the technology of conventional power generation has adversely affected the environment, as a larger percentage of the generation is dependent on the process of combustion of fossil fuels. Moreover, wide scale excavation of mines and cutting of forest, has added both to the degradation of
environment and depletion of global fuel reserve. Therefore, alternative sources of energy, which have the advantages of being both clean and renewable in nature, have attracted the researchers in their potential for electrical power generation. With the integration of larger capacities of power generation from alternative sources like renewable energy, the importance of operation and control of conventional power systems with integrated renewable energy sources has increased. Because, the nature of intermittency in renewable sources based power has added newer challenges for the reliable system operation. In this context, the importance of system operation with integrated WECS, has become important and needs to be clearly understood.

1.3.1. Operation of Electric power system in the presence of wind power

In recent past, the effect of wind turbine generators on performance of power system was of marginal importance, because the penetration level of wind power was low and most of them were either not integrated with the grid or they were of smaller in capacity. But, with greater penetration of wind power into the grid, the operation and control of the later has been studied with more rigour. Larger share of wind power has been found [9, 10] to affect the power flows and node voltages of the system. With a proper strategy, the conventional generating units are replaced by wind power plants (WPP) to contribute to system voltage control. However, the unpredictability of wind flow results in improper estimation power generation capacity. The error of estimation may become large with increased scale of wind integration, which may lead to insecure system operation. An improper planning of their utilization may lead to problems related to both frequency and voltage. To comprehend the effects with some clarity, it is necessary to understand the fundamental concepts of power generation in WECS.
1.4. THE CONCEPT OF WIND POWER GENERATION IN WECS

The principle used in WECS is to convert the kinetic energy of the wind resource to mechanical form of energy. Wind turbines capture the kinetic energy from the aerodynamic power of wind energy and transform it to the mechanical form. The conversion of energy from mechanical to electrical form is done by the generators installed and driven by wind turbines. The rotating shaft of the generator that is coupled to the wind turbine shaft through gears drives mechanical energy collected from the later and converts the same to electrical energy. It is not always necessary to connect the low speed shaft of the wind turbine 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.

In a wind generator, the power cable transmits electrical power to a transformer. The voltage from the generator is generally in the range of a few hundred volts. The transformer connected to the generator, steps up the generated low voltage to the distribution or sub-transmission levels. The generated power that is proportional to the kinetic energy ($E$) of the wind, can be expressed in terms of the flowing air mass $m$, and its velocity $v_w$ as follows

$$E = \frac{1}{2} m v_w^2$$  \hspace{1cm} (1.1)

Further, the instantaneous power derived from the wind flowing through an area ‘A’ with air mass density $\rho_a$ can be expressed as

$$P_w = \frac{1}{2} \rho_a A v_w^3$$  \hspace{1cm} (1.2)

Because, the air mass per second can be expressed as

$$m = \rho_a A v_w$$  \hspace{1cm} (1.3)

In a variable speed wind turbine, the rotor blades rotate freely in accordance with the speed and direction of the wind. The power extracted from the wind is dependent on the rotor power efficiency to capture the aerodynamic power. This is based on the fact that the speed of
the wind flow after passing through the rotor blades cannot become zero, which leads to efficiency less than 1. As per Betz limit, the mechanical power captured by the wind turbine depends on the rotor power efficiency of the turbine, which can be represented as

\[ P_{turb} = \frac{1}{2} C_p (\lambda, \beta) \rho_a A v_w^3 \]  

(1.4)

The rotor power efficiency of the turbine \( C_p \) is the function of the blade tip speed ratio \( \lambda \) and blade pitch angle \( \beta \). In order to avoid any wake effect, the two wind turbines are mounted at a distance that is equal to at least three times that of their rotor radius from one another. If the tip speed ratio is less than 3, the wake effect reduces the maximum rotor power efficiency.

The tip speed ratio can be calculated as

\[ \lambda = \frac{\omega_b R}{v_w} \]  

(1.5)

Where \( \omega_b \) the rotor speed in radian/sec. R is is rotor radius from axis to tip in meter.

**1.4.1. Configuration of wind farm**

A wind farm is comprised of a number of wind turbines up to a few MW which can be located both onshore and offshore depending upon the availability of wind. The offshore wind farm generates more stable power than onshore wind farm because the wind speed is higher and consistent. Furthermore, a WECS can be operated in a grid connected or standalone mode. In remote areas, a group of small wind turbines supply the electrical power to households or business buildings separated from the grid. Even though the initial installation cost is high, it may be worth investing, as they provide electrical power for a considerably long duration. Among different categories of wind turbines, the ones having variable speed mitigate the problems of the mechanical stresses. Because of the variable magnitude and frequency of power outputs from the variable speed wind turbines, there must be a power electronic interface for successful grid integration to decouple the power outputs of the wind turbines to the grid. Different types of generation systems for WECS are discussed as follows.
1.4.1.1. Generators

There are different types of wind power generators [11] in use today. The main distinction can be made between fixed speed and variable speed types of wind generators, as mentioned below.

1.4.1.1.1. Fixed speed wind turbine generator

In the early stage of wind power development, most wind farms were equipped with fixed speed wind turbines and induction generators. In this arrangement, as the induction generator runs at slip speed, a gearbox is required to match the speeds of the turbine and generator. The fixed speed generators have a design specified speed for which they have maximum efficiency. A fixed speed wind generator is usually equipped with a squirrel cage induction generator whose speed variations are limited. Power can only be controlled through pitch angle variations. The power generated from a fixed speed wind generator varies directly with the wind speed, because the efficiency of wind turbines depends on the tip-speed ratio. Moreover, power factor correction systems may be essential for compensating the reactive power demand of the generators, because the induction machines have no reactive power control capabilities. Fig. 1.6 depicts the general constructional layout of a fixed speed wind turbine.

![Fixed-speed wind turbine with an induction generator](image)

Fig. 1.6. Fixed-speed wind turbine with an induction generator.

1.4.1.1.2. Variable speed wind turbine generator

Several technologies and applications of variable speed wind generator have been discussed in [4, 11]. Variable speed generators have the maximum power tracking capability
that extracts maximum available power out of the wind at different speeds, resulting in more efficient operation. Further, the variable speed generators reduce mechanical stresses on the turbine, which increases its lifetime. These generators also have the advantage of damping out oscillations in torque in a more efficient manner. Therefore, generally the variable speed generators are preferred over fixed speed ones.

![Diagram of wind turbine with variable speed generator](image)

Fig. 1.7. Variable-speed wind turbine with a synchronous/induction generator.

Fig. 1.7, depicts one of the schemes of variable speed generators driven by wind turbine. It can be recalled that, most of the rotating industrial loads driven by electrical power, utilize induction motors. The primary advantages of the induction machine are its rugged brushless construction that avoids the need of separate DC field power. The disadvantages of both the DC machine and the synchronous machine are eliminated in the induction machine, resulting in lower capital cost, maintenance, and better transient performance for a variable speed operation. Therefore, the induction generator is extensively used in small and large wind farms and small hydroelectric power plants. The machine is available in numerous power ratings up to several megawatts capacity, and even larger.

The induction machine needs AC excitation current, which is either self-excited or externally excited. A standalone induction generator system is self excited by shunt capacitors, because the excitation current is mainly reactive in nature. Alternatively, the induction generator connected to the grid draws the excitation power from the network. From the point of view of economy and reliability in operation, many wind power systems use induction machines as
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The electrical generator. One of the most widely used variable speed wind generator concepts is the doubly fed induction generator (DFIG) that is used in this work.

1.4.1.1.2.1. Doubly fed induction generator (DFIG)

The scheme of DFIG is shown in Fig.1.8. It consists of a wind turbine that is connected via a gear train to the rotor shaft of the induction generator. The rotor terminals of the induction machine are connected to the four-quadrant power electronic converter capable of supplying both real and reactive powers from the grid to the rotor as well as supplying power from the rotor to the grid [11]. There are two different converters as depicted in the Fig. 1.8. The converter connected to the rotor of the induction generator is the generator side known as Rotor Side Converter (RSC) and the one connected to the grid side is known as the Grid Side Converter (GSC). In the figure below RSC and GSC are denoted as $C_{\text{rotor}}$ and $C_{\text{grid}}$ respectively.

![Fig. 1.8. Variable-speed wind turbine with a doubly-fed induction generator (DFIG).](image)

Both of these power electronics converters have different functions and they are interconnected with a common DC link capacitor. The GSC controls the real and reactive power output of the machine and the GSC maintains the DC link voltage at its set point. These converters are controlled by their respective controllers, which derive the converter firing pulses following their own control laws. The wind turbine of the DFIG also has a
controller that maximizes the power output from the turbine via pitch control and sends this computed maximum power output as reference input to the converters. The GSC is connected to the grid via a transformer that steps up the voltage to the grid. The stator side of the induction generator is also connected to the grid via a step up transformer. The point of interconnection with the grid is the point used to measure the active and reactive power output of the wind farm. For reliable operation of the system, additional reactive power can be injected by incorporating a compensating unit. The RSC of the DFIG injects suitable magnitude and phase of voltage in three phase rotor windings via the slip rings and brushes. The magnitude and phase angle of the injected voltage that is derived from the RSC, are decided in such a way that the RSC can facilitate power flow in both the directions to operate the DFIG both at sub synchronous and super synchronous speeds. The DFIG produces controlled voltage $V_1$ at the grid frequency $f_1$ in the stator and variable voltage $V_2$ at a variable slip frequency $f_2$ in the rotor. The frequency of the rotor depends on the angular velocity of the rotor which in turn depends on the wind speed or slip. Let $f_r$ be the electrical frequency of revolution of the rotor. The following relation holds between the various frequencies:

$$f_r = f_1 \pm f_2$$  \hspace{1cm} (1.6)

The positive sign above is for the super synchronous operation where rotor speed exceeds rated speed and a negative sign signifies a sub synchronous operation, when rotor speed is less than the rated speed. At super synchronous speed, the phase sequence of the rotor currents is the same as the stator and power is supplied from the rotor to the grid. In the sub synchronous operation power is drawn by the rotor from the grid and the phase sequence of rotor currents is opposite to the phase sequence of the stator currents.

The steady state operation of the DFIG is only restricted by the converter ratings of the RSC. The maximum power rating of the same ($P_{max}$) is generally in the range of 25% to 30%
of the induction machine ratings. Therefore, if the converter is operated in such a manner that all magnetizing power is provided by the stator, the maximum rotor power supplied/absorbed is $P_{\text{max}}$. The rated power output of the DFIG is $P_{\text{rated}}$ and the maximum magnitude of slip for operation is given by (1.6). It follows that, the DFIG can provide an operating range of 75% to 125% of the rated wind speed.

$$S_{\text{max}} = \frac{P_{\text{max}}}{P_{\text{rated}}}$$

Further, the pitch control with a maximum power tracking allows the DFIG to produce maximum power at both sub-synchronous and super synchronous wind speeds; thereby increasing overall efficiency of the unit. The detailed modeling aspect of DFIG is described in section 2.2.1.

In all the technologies of generators in general, as the power output of WECS is directly dependent on wind speed, so the analysis of wind speed and its characterization becomes an important issue for a complete understanding. That is discussed in the next section.

1.5 CHARACTERIZATION OF WIND SPEED

The most challenging issue for the integration of the wind power into the grid is its variability. Therefore, the prediction of wind power output plays an important part in the system integration of large-scale wind power generation. Wind power production is highly dependent on the variability of wind resources at the site. The distribution of wind flow depends upon the seasonal and the geographical area. Wind prediction has been investigated by many researchers in variety of ways. The methods of prediction are based on time series [12,13], fuzzy logic [14], neural network [15], artificial intelligence etc, which have their own unique features and degrees of accuracy. Various methods of wind power forecasting are demarcated into two broad categories, i.e., the Persistence model and the Numerical weather prediction (NWP) [16], as shown below.
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Wind power Forecast (WPF)

\[
\begin{align*}
\text{Persistence Model} & \quad \text{Physical Approach} \\
\text{WPF with NWP} & \quad \text{Statistical Approach}
\end{align*}
\]

The persistence model is known as the simplest way of forecasting the wind power output. It assumes that the future wind generation at \( t + t_0 \) will be the same as it was at time \( t \). The method is easy to implement, and it is usually used as a benchmark for evaluating the performance of advanced forecasting tools. The accuracy of this method is largely reduced with increase in time of prediction. However, in the shorter time scale [17] (several minutes to few hours) it was found that, this simple method performs even better than the NWP tools.

There are two main approaches to NWP, i.e., physical and statistical approaches. They differ in their methodologies of converting forecasts of meteorological variables to predictions of wind power output. The physical approach collects sufficient information of meteorological parameters and down-scales the wind speed and its direction to the height of the turbine hub. It then analyses the information with complex computation, and use the power curve to get an estimation of the wind power output. The requirement of acquisition of a large amount of meteorological information and the complexity of its computation, limit the feasibility of physical approach in the short-term forecast (several minutes to hours). In practice, the performance of physical approach is often satisfactory for longer periods (more than 6 hours ahead). Alternatively, the statistical approach directly translates the input meteorological variables into the capacity of wind power generation without considering the physical transformation procedures. It is done with a statistical block whose parameters are estimated by using the relation between historical meteorological predictions and power output. This statistical block combines the inputs i.e., NWPs of the speed, direction, temperature, together with the online measurement of wind power, speed, and direction etc. The method then gives out a direct estimation of regional wind power from the input parameters.
Unfortunately, the statistical data are not stationary and there are weak variations and changes, which may lead to very inaccurate results. Until recently, almost all the programs of prediction use at least one of the two methods of prediction of wind power i.e., the physical and statistical methods. In the models involving the physical methods, the wind farm equations are formulated according to the aero dynamical behaviour of wind turbines. This can be understood as the local effects of wind speed and direction at the actual site. However, the statistical methods try to reproduce the behaviour of the wind farm from the past data under different conditions. Physical models usually require long computational time compared to the statistical method.

For the statistical analysis, several probability distribution models [18] were either used or proposed for the for the prediction of the recorded wind speeds. Researchers have investigated the fitting of specific distribution to wind speed. Among them, the most widely used probability density function (pdf) to describe the wind speed is the Weibull functions [19,20]. Because, the pdf of the wind speed profile at a given location most closely follows a Weibull distribution over time. The pdf for Weibull distribution is given by

\[ f_v(v) = \left( \frac{k}{c} \right) \left( \frac{v}{c} \right)^{k-1} \left( e^{-\left( \frac{v}{c} \right)^k} \right) \]  \hspace{1cm} (1.8)

where

- \( V \) - Wind speed random variable
- \( v \) - Wind speed;
- \( c \) - Scale factor at a given location (units of wind speed);
- \( k \) - Shape factor at a given location (dimensionless).

The Weibull distribution function with a shape factor \( k \) of 2 is also known as the Rayleigh distribution. According to [20], the advantages of the Weibull distribution are noted as follows

i) It provides a good fit to the observed wind speed data
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ii) If the shape factor $k$ and scale factor $c$ are known at one height, it is possible to find the corresponding parameters at another height.

Generally $k$ and $c$ vary from within ranges of 1 to 3 and 5 to 25 respectively. Fig. 1.11 shows the variation of distribution pattern of wind speed when the above mentioned parameters are varied within the above stated ranges.

1.5.1. Relation between the wind speed and wind power

After the wind speed is characterized as a random variable, the output power of the WECS can also be determined as a random variable utilizing a transformation that converts wind speed to wind power. Based on the operational limits of the WECS, the power output of the wind turbine generator (WTG) are assumed to vary in three ranges defined as follows

(i) Below the cut in wind speed ($v_i$) and above the cut out wind speed ($v_o$).
(ii) Between $v_i$ and the rated wind speed ($v_r$).
(iii) Between $v_r$ and $v_o$.

From the relations (1.9)-(1.11) it can be summarized that, WECS has no power output for wind speed below $v_i$ and above $v_o$. A linear power output relationship exists for wind speed between $v_i$ and $v_r$. Finally, a constant rated power output is derived for wind speed between $v_r$ and $v_o$. The limitation of not operating the turbine above $v_o$, facilitates a safe and reliable operation of the WECS as the entire system is shutdown above this speed.

Similarly, when the wind speed is low, the blades of wind turbine would not rotate due to the friction and large inertia, and no electricity can be generated. But, when the wind speed is greater than some minimum value, the blades have enough capacity to produce torque and start generating power. The value of $v_i$ is typically between 3 to 5 m/s. Alternatively, if the wind speed is allowed above $v_o$ then it may damage the rotor and therefore the self-protection
system of the turbine operates to shut down the rotor. Mathematically, the power output of WECS within the above ranges can be expressed as

\[ p = 0, \quad \text{for } v < v_i \text{ and } v > v_o \]  \hspace{1cm} (1.9)

\[ p = p_r \times \frac{(v-v_i)}{(v_r-v_i)}, \quad \text{for } v_i \leq v \leq v_r \]  \hspace{1cm} (1.10)

\[ p = p_r, \quad \text{for } v_r \leq v \leq v_o \]  \hspace{1cm} (1.11)

The above relations are plotted in Fig.1.9 using the MATLAB.

Fig.1.9. Variation of wind power with wind speed
From the equations in 1.9-1.11 it is clear that, the WECS power output varies linearly with the wind speed between the range of \( v_i \) and \( v_r \), at which it attains its rated value and remains constant at that value till \( v_o \). Therefore, for all ranges of speed the power has discrete values that are mixed and discrete in nature. Two discrete probability events occur when there is no wind power output and rated power output. Mathematically, the above two events may be represented as (1.12) and (1.13) respectively. Probability of the event wind power \( (P_w) = 0 \) is

\[
P_r (P_w = 0) = P_r (V < v_i) + P_r (V \geq v_o) \]

\[
= F_r (v_i) + (1 - F_r (v_o))
\]

\[
= 1 - \exp \left( -\left( \frac{v_i}{c} \right)^k \right) + \exp \left( -\left( \frac{v_o}{c} \right)^k \right)
\]

(1.12)

Fig. 1.10. Weibull mixed probability function for different wind speed.
Similarly, the probability of event $P_w = P_r$ is

$$P_r (P_w = P_r) = P_r (v_r < V < v_o)$$

$$= F_V (v_o) - F_V (v_r)$$

$$= \exp \left( - \left( \frac{v_r}{c} \right)^k \right) + \exp \left( - \left( \frac{v_o}{c} \right)^k \right)$$

(1.13)

In Fig. 1.10, the discrete and continuous portions of the wind power probability functions based on the Weibull wind speed pdf with $k = 2$ and $c = 10, 15, \text{ and } 20$ are plotted using MATLAB. As the value of $c$ in the Weibull distribution function is increased, a greater proportion of the wind speed profile is located at higher values of wind speed. Higher values of wind speeds, result into a lower discrete probability of zero power, a higher discrete probability of rated power, and a smaller amount of power in the continuous portion of the plot. Similar to any other mixed discrete and continuous probability function, the sum of the discrete probabilities at zero and rated power, and the integral from 0 to 1 of the continuous function will be equal to 1.
The converters used in most of the WECS technology including the DFIG, use power electronics switches, which have limited capacities of current and voltage. Therefore, these converters also have limited real and reactive power managing capacities. During the system operation with these constraints, the role of FACTS devices may be important, which is discussed briefly in the following section.

1.6. FLEXIBLE AC TRANSMISSION SYSTEMS

Advances in Flexible AC Transmission Systems (FACTS) devices [21, 22] improve power system operation and control both during steady and dynamic state conditions. Extensive research in these devices has shown their efficacy in improvement of reliability and stability of large interconnected power system. Owing to their ability to control all the
parameters like series impedance, shunt impedance, voltage, current, phase angle which
govern the power flowing in the transmission systems, the FACTs devices have improved the
controllability of both real and reactive power. According to the structure of their construction
and usage FACTs devices can be classified as

i) Series Connected devices
ii) Shunt Connected devices
iii) Combined series-series devices
iv) Combined series-shunt devices

These devices are discussed in brief in the following sub sections.

1.6.1. Series Connected Devices

The main function of these types of devices along with their controllers, is to inject a
voltage in series with the line. The series devices either compensate the line reactance by
including a variable inductive or capacitive reactance in the line, or they have power
electronics based variable voltage source converters injecting voltage in series with the line
voltage. In the later case, when the injected voltage has non-quadrature phase relationship
with line current it requires real power to maintain the injected voltage, otherwise it utilizes
only reactive power. Among different types of series connected devices, the Thyristor
Controlled Series Compensator (TCSC) and Static Synchronous Series Compensator (SSSC)
have become more popular in terms of their applicability. The main applications are as
follows

• They reduce the magnitude of transmission line voltage drops by changing the bus voltage
  magnitude or angle or both.

• Voltage fluctuations are reduced when transmission line power changes.

• They improve the dynamic performance of any system with better damping of oscillations.

• Short circuit currents are limited in networks or substations.
Introduction

The TCSC addresses specific dynamical problems in transmission systems. It increases the overall damping in a large interconnected system. The TCSC's high speed switching capability provides a fast mechanism for controlling line power flow, which can rapidly increase and readjust the line power flows in transmission lines. The above facet, improves the overall dynamic performance of the system, even in increased stressed conditions. Alternatively, the SSSC by injecting a suitable voltage in series with the line voltage can achieve similar or sometimes even improved performances compared to the TCSC. The configurations both the devices are demonstrated in Fig.1.12.

Fig.1.12 The Series Connected FACTS Devices

Fig.1.13 The Shunt Connected FACTS Devices
1.6.2. Shunt Connected devices

Primarily, the shunt connected devices inject a variable shunt current into the line at the point of coupling of these devices. Similar to the different structures of series connected devices, shunt devices may either have variable shunt impedance or variable shunt connected voltage source converters. Among different types of shunt connected devices, the usage of the variable impedance type of Static Var Compensator (SVC) and the variable voltage source type of Static Synchronous Compensator (STATCOM) are more popular. In all these devices, as long as the injected current is in quadrature with the bus voltage, it will supply or demand only reactive power. Therefore, the shunt devices operate generally as reactive power compensators. Their main applications in transmission, distribution and industrial networks are as follows:

- They restrict the excessive reactive power flows in transmission lines reducing losses.
- Help in maintaining the power exchange contracts with balanced reactive power.
- The issues of power quality with considerable fluctuations in load demand are alleviated.
- They improve both steady state and transient stability of power system.

![UPFC Scheme](image)

Fig.1.15 The Series-Shunt Connected FACTS Devices
1.6.3. Combined Series Series Connected devices

These devices use two or more numbers of series connected devices, which are placed at different transmission lines in the system but operate in a coordinated manner. The most widely used device in this category is termed as the Interline Power Flow Controller (IPFC). In the case of the IPFC, more than one series connected devices are placed in different transmission lines present in a system. The use of IPFC optimizes the utilization of transmission systems effectively by controlling both real and reactive power flows in the lines. In these controllers the DC terminals of all of them are connected together for an effective control of real power demands in different lines.

1.6.4. Combined Series Shunt Connected devices

In the combined series shunt types of devices, two converters are placed at the same bus and act in a coordinated manner. The shunt converter injects current at the point of coupling and the series converter injects voltage in series with the line voltage. A very widely used example of this type of device is the Unified Power Flow Controller (UPFC), where the series and shunt converter units form a unique combination of SSSC and STATCOM operating simultaneously in the system. For a coordinated and smooth control, both of them are connected to a common DC-link capacitor as shown in the Fig.1.15. The real power exchange between the series and shunt parts is done via the DC link.

With above background of fundamental concepts, it is essential to investigate into some more detail of literature of past research, in the field of operation and control of WECS integrated power system and its supporting devices.

1.7. LITERATURE REVIEW

The modeling and formulation of different types of steady state and dynamic problems in wind integrated power systems are different in their approach, compared to those systems
Introduction

utilizing only conventional sources. The problem of real power generation scheduling in an integrated system, requires inclusion of the nature of intermittency of wind flow. The issues and constraints related to the conventional generators have also to be included during the scheduling stage. If the amount of wind flow profile and the power available from it were known with certainty, then the cost of wind power generation can be found directly in a simpler way [23]. The cost of generating wind power in this way is known as the direct cost of generation. However, with variable nature of wind flow, the scheduled power from WECS cannot be assured to match with the power available from wind energy. To overcome the problem of wind power uncertainty, additional cost components may be added during the scheduling problem. The study in [24], has dealt with the random variation of available wind power, by adding penalty and reserve costs to the direct cost of generation. Two different scenarios of improper estimation of available wind power (WP), i.e., under estimation (UE) and over estimation (OE), is reported in [23]. The generation scheduling problem is extended to be formulated as a multi objective optimal power flow (OPF) problem that includes some economic and environmental constraints [25]. The effects of stochastic nature of wind flow, on the unit commitment and dispatch of power systems are examined in [26]. Authors in [23, 27] have considered and explained the role of various cost components in generation scheduling, when a large percentage of wind power penetrates into conventional power system. In [28], Xu. M et.al. have developed a strategy for evaluation and incorporation of optimum wind power capacity in power system. Even though different conventional [73-75] and heuristic intelligent techniques[29-37] based optimization tools are suggested for solution of the problem of OPF in power system. The work limits itself to the later category only. In this regard, some past research are discussed below.

The work in [29] presents an enhanced genetic algorithm (EGA) for the solution of the optimal power flow (OPF) with both continuous and discrete control variables. The
continuous and discrete control variables modeled are unit active power outputs, generator-bus voltage magnitudes and transformer-tap settings respectively. The main goal of another study [30], is to verify the viability of using simulated annealing (SA) to solve the OPF problem simultaneously composed by the load flow and the economic dispatch problem. Similarly researchers in [31-33] have developed models where optimal operating conditions are obtained after the implementation of linear programming, differential evolution (DE), and bio geography based optimization (BBO) techniques respectively.

Vaisakh in [34] has proposed an evolving ant direction based differential evolution (EADDE) algorithm, for solving the optimal power flow problem with non-smooth and non-convex generator fuel cost characteristics. In another study [35], the artificial bee colony (ABC) algorithm is employed as the main optimizer for optimal adjustments of few power system control variables within the OPF framework. Moreover, different objective functions such as fuel costs, total active power loss, voltage profile improvement and total emission cost are chosen for this highly constrained nonlinear multi objective optimization problem. With an objective to minimize the cost of power generation with different linear and non-linear constraints, authors in [36] have presented an efficient and reliable evolutionary based approach to solve the optimal power flow (OPF) problem. They have employed the integration of fuzzy Systems with genetic algorithm (GA) and particle swarm optimization (PSO) algorithm for solving the OPF problem. To overcome the demerit of large computational time involved in finding optimum solution, a method of parallelization of PSO algorithm is demonstrated in [37]. The algorithm is applied in determining the optimal power system operating conditions.

All the above discussed studies have focused on solving various issues related to power generation with conventional (thermal) generating units only. Penetration of wind power with conventional power generation aspect has not been taken into consideration by any of the
above works. In some early works in the field of inclusion of WECS in the scheduling problem of thermal system, the authors in [14] have developed an economic load dispatch model with several constraints of WECS being modeled by a fuzzy based approach. Few more similar researches [38-46] have focused their attention on incorporation of stochastic variation of wind power in economic load dispatch (ELD) or economic emission dispatch (EED) framework. In this regard, X. Liu, W. Xu et al. have developed realistic models of wind integrated systems on different time frame/scheduling horizons[38-40]. A dual decomposition algorithm is applied in [41], for solving a stochastic program for committing reserves in systems with large amounts of wind power. The wind power generation is modeled in terms of a representative set of appropriately weighted scenarios and with their respective dual variables. Considering the load and wind power production as stochastic inputs, the system operating cost is minimized by using mixed integer linear programming in [42]. Impact of wind power penetration [43] on system operation and emission reduction in economic dispatch environment is investigated by authors using Quantum-inspired particle swarm optimization (QPSO) [44], Gravitational search algorithm (GSA) [45], Sequential quadratic programming particle swarm optimization (SQPPSO) [46], Hybrid imperialist competitive-sequential quadratic programming (HIC-SQP)[47].

In addition to the above reported studies focused on real power generation issues in WECS, the problems related to limited supply of reactive power ($Q$) resources in these systems is probed in [48]. It is found that, an improper management of these resources might make the system voltage insecure, particularly during the operational stages of integrated systems with higher penetration of wind power. In this context, the $Q$ planning [48], the cost of its resources [49], determination of approximate availability of $Q$ [50] and the effects of $Q$ on static voltage stability [51, 52] of the system, are important. Similarly improvement of system voltage stability by $Q$ rescheduling [53], and application of modified NSGA-II
algorithm to reactive power planning in multi-objective optimization problem is discussed by authors in [54]. Moreover, with considerable amount of DFIG based WECS units having limited reactive power generating capacities [55-57] operating in the system, the system may be forced to operate in a voltage insecure manner under overloaded and stressed operating conditions. Hence, it may be necessary to give local reactive power support both at the DFIG buses and some weak nodes in the network. Conventionally, apart from reactive power supplying capacity of fixed capacitors, the role of shunt FACTS devices like static VAR compensators (SVC) and STATCOM have been extensively investigated [58-60]. STATCOM has been found to be more beneficial compared to SVC, as it has better operational flexibility towards improving the dynamic performance of the system, giving better reactive power support [61] and enhancing the low voltage ride through (LVRT) capability of wind farm [62]. The device has been extensively utilized to achieve wide range of objectives like rapid voltage control [63], damping of the oscillations [64] and improving the loading margin [65, 66] in power system. However, most of these studies have been carried out in systems with either conventional power generation sources. In some earlier works [63], the role of STATCOM in improving dynamic performance of the WECS connected to the grid is studied. The steady state issues during generation scheduling may not have been studied widely. Moreover, with wider wind penetration with WECS having limited reactive power capacities in the system, the later may be prone to static voltage instability during increased load conditions. Therefore, the function of STATCOM with the environment of limited reactive power capability of WECS may need further attention, particularly when the penetration levels of wind power in the grid is gradually increasing.

Probing into the reactive power capabilities of DFIG based WECS, the authors in [67] have shown that during under estimation of wind power, the reactive power ($Q$) capability of DFIG may limit the system’s ability to maintain secure system bus voltage. To address the
security concerns in the system, the authors have formulated a security constrained economic dispatch in DFIG based WECS where reactive power capability of DFIG has been analyzed. The study in [68] presents P-Q curves of DFIG for different terminal voltages by considering only rotor current limits. Lund et al. [69] derived P-Q curves of a DFIG by imposing rotor current, stator current, and rotor voltage limits. But they have not considered the reactive power capability of the GSC, which can substantially restrict the operating range of a DFIG. Considering these aspects, a complete model of reactive power capability of DFIG converters is presented by authors in [56, 57].

In addition to the aspects discussed in [67, 70], this study has attempted to validate the role of STATCOM and local reactive power (Q) generating sources to obtain an optimum real power generation schedule. The focus of the work is not only to obtain an optimum generation cost both of the thermal units and the WECS, but also to do so in voltage secure manner using a STATCOM placed at the weakest node [71] in a test system. The problem is formulated in an OPF framework [72] with an objective to minimize the generation cost of both the types of generators. Additional cost components related to total reactive power requirement ($C_{VS}$) by the system, which is to be supplied by either local Q-generating sources at WECS buses or STATCOM or both of them, are added. In OPF, the inclusion and impact of these additional factors on the system parameters has been analyzed under different scenarios. OPF problems, when formulated in the optimization domain, have been extensively solved by several conventional [73-75] and intelligent technique based algorithms [29-37]. Limitations in some of the above discussed studies have motivated the present work to explore the following aspects and objectives.
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1.8. OBJECTIVE OF PROPOSED WORK

The main objectives of the proposed work are

- To formulate the problem of economic dispatch in a WECS integrated IEEE 30 bus test system, in the domain of OPF. The formulation considers different stochastic costs involved in improper estimation of available wind power. Further, the reactive power limitation constraints of DFIG based WECS is considered. After optimization, the resulting schedule should also be able to operate the system in a voltage secure manner during stressed operating conditions.

- In addition to the local support of reactive power at the DFIG buses using fixed capacitors, the role of a STATCOM for the same purpose is to be sought. All the available reactive power resources in the system including the STATCOM, are aimed to operate in a coordinated manner so that maximum benefit out of them could be derived.

- The operation efficiency of the above optimized schedules is tested particularly from the voltage security aspect, under conditions of increased load and N-1 contingency criteria.

- Proceeding with the above approach, further constraints like the environmental emission is to be tested. The effect of this constraint on wind thermal scheduling and the operation of STATCOM need to be understood.

- With a motive to include and extend varieties of distributed generation resources, hydro based sources may also be added in a wind-thermal-hydro scenario. The role of STATCOM and other resources in this scenario may be probed.

- For optimizing the formulated problems in different chapters, an optimization algorithm that is relatively recent and has been shown to perform uniformly in many
of the optimization problems in power system, is sought. Necessary modifications in
the same algorithm to expedite convergence may be done.

The thesis is organized in the following manner.

1.9. ORGANIZATION OF THE THESIS

The thesis consists of six chapters.

Chapter 1 Introduction

The ongoing chapter 1 explains the necessity and role of renewable energy sources in power
system operation. Further, it introduces various issues associated with WECS when they are
integrated with an existing power system. It elucidates the basics of an WECS briefly over
viewing its constituents, and scheduling of WECS. Topics related to uncertainty of wind flow
and its solution methodologies are also explained along with the roles of FACTs devices in
system operation. At the end, it presents a critical analysis of the past research work in this
area, deriving motivation of the present work from them.

Chapter 2

This chapter the methodology involved in OPF formulation in a wind integrated test system is
explained. The IEEE 30 bus benchmark test system, with some of the small capacity
generators assumed to be replaced by wind farms, is introduced. The problem formulated as
OPF, optimizes the cost of generation of both thermal and wind units, so that it could manage
both economical and reliability issues simultaneously. Evaluation of various costs involved to
reflect the intermittent nature of wind power is done and various constraints and the technique
to handle them, is presented in this Chapter. Thus the formulation of objective function for the
wind thermal generation system is done so that the system, when subjected to (N-1)
contingencies could be operated in a voltage secure manner. Various optimization tools for
evaluation of the above systems are described.
Chapter 3 depicts the results for the wind-thermal generation system with the incorporation of shunt FACTS device, in the form of STATCOM at the weakest bus of the test system. It highlights the gains in terms of voltage security and operational efficiency achieved in the system compared to the case when system is operating without a STATCOM.

Chapter 4 develops a model of wind-thermal generation system while focusing on the reduction of emission, by optimum utilization of available wind power. Thus, an environmental OPF model is developed and the optimal solutions are obtained with Hybrid intelligent optimization technique. The results are compared with some other established heuristic optimization methods.

The results of scheduling of wind-thermal generation system with the inclusion of hydro power generation unit in a hydro-thermal-wind environment are depicted in Chapter 5.

Chapter 6 summarizes the entire work, which contains the conclusions drawn from the present work, their limitations and recommendations for future work.