CHAPTER 1

INTRODUCTION AND PREVIEW

The energy utilization has always been of significant importance looking into the history of humankind. From the beginning, humans have searched for ways to extract the energy available either by rubbing the stone to light the fire or relying on the firewood for cooking purpose. With the advancement and development, the kind of resources human relied on changed and has been changing even today. Science and technological progress have made today's age very much more accessible but at the expense of energy. The primary source of energy extraction till date has been the petroleum extracts. These sources are going to dry up now and then looking into the developmental works that have been carried forward at present age. Also with the growing population has caused the increase in the industrial and domestic demands of energy and resources. In the planet of limited resources, such growth in demand can cause the exhaustion of the earth's energy resources [1]. Long ago, the need to generate large amounts of electrical energy and the realization that giant power plants were more efficient than smaller ones encouraged the construction of massive power plants. However, the construction of such bigger plants accompanies with massive floods, large power transmission lines, and towers, air pollution, modified waterways, devastated forests, etc. This trend in development has caused the material capacities to reach their limits and widespread, increasing pollution. The novel alternative has to be device if humankind is to stay alive today, moreover for centuries to come. In the ancient times century, it has been seen that the expenditure of non-renewable sources of energy has caused an ecological damage than any other human activity. Electrical power generated from fossil fuels such as coal and crude oil has led to the high attentiveness of harmful gases in the atmosphere. It has, in turn, resulted in a lot of problems being faced nowadays such as ozone exhaustion along with global warming. Vehicular toxic waste has also been a significant problem [2]. Consequently, alternative sources of energy have become very relevant and applicable today's world. These sources, such as the sun as well as the wind, can never be fatigued and consequently are called renewable sources. Generally of the renewable sources of energy are relatively non-polluting and considered clean though biomass, a renewable source, is a significant polluter indoors. The source of energy which comes from natural resources such as sunlight, wind, rain, tides, and geothermal heat, and is naturally renewed is termed as renewable energy. Renewable sources of energy have been in the limelight considering the advantages they offer and also the technical and economic benefits entailed with them. Even though renewable in nature, it is of utmost importance to search for the best method that can maximize the power extraction from any chosen renewable source. Therefore, it also becomes necessary to look into the best ways that can increase the extraction to available energy ratio with the use of proper technology. Wind power is the exchange of wind energy into an appropriate form of energy, for instance using wind turbines to generate electrical energy, windmills for mechanical power, wind pumps for water pumping, or sails to drive ships. The whole amount of cost-effectively extractable power available from the wind is significantly more than present human power use from all sources. Wind power, as an option to vestige fuels, is plentiful, renewable, extensively extent, clean, and produces no greenhouse gas emissions for the duration of the process. Windpower is the world's fast-growing source of energy [3]. The favorite of electricity is generated by burning coal, rather than an eco-friendlier scheme like hydroelectric power. This use of coal causes untold ecological harm through CO_2 and other toxic emissions. The energy division is by far the largest source of this radiation, together in the India as well as globally, and if we are to tackle climate change, it is evident to move limited fossil fuel reserves to more sustainable and renewable sources of energy. The beneficial characteristics of wind energy include Clean and endless fuel, Local economic expansion, Modular and scalable technology, Energy price stability, Concentrated dependence on imported fuels.

1.1 An Overview of Wind Energy

Renewable resources are precious, and they are naturally available all over the world. The increase in renewable energy sources mode could make energy market independent of fuel price fluctuations. Switching to renewable resources as well economic profits can fetch other benefits such as clean atmosphere and less climate change by falling greenhouse gas discharge [1]. Advanced wind turbines availability is usually more than 98%, and in a proper stormy region, they can perform with capacity factors of 35–40%. Furthermore, over the last decades, the price of wind-based electrical energy has settled about 90%. Subsequently, a new vast wind farm which constructed at a windy site can generate electricity at the cost of 4–6 ¢/kWh (U.S. dollars Wind energy is the fastest-growing energy source in the world. This renewable and neat source has forever been obtainable and had a background for more than 3000 years old, whereas it employed for electrical energy production about 120 years ago [4]. Wind technology presence in electric power production field has been highlighted for the first time during the 1970s oil crisis. The worldwide trend toward clean energy is an inspiration for more integration of wind-based electric power in power systems [5]. Vast and small wind turbines produce electric power for networks and usefulness’s whereas they sustain stand-alone isolated areas like well [6].

1.2 Past background of wind energy

The custom of wind energy has a longer chronicle, about 3000 years before Persians, as well as Egyptians, began utilizing this energy for lifting water even before coal and refined oil discovered. Moreover, they attach windmills likewise water wheels to pulverize wheat and rice, centuries previous to the Europeans. Likely, the first wind generator constructed in Scotland by Professor James Blyth in 1887. On the next year during 1888, the first usable wind machine was originated by Bruch as well as his work fellows and established on the Atlantic shore; the span of that turbine was 17 m. Furthermore, it was able to with 81 cedar blades. It produced only 12 kW and also want to charge batteries as DC supply used for lamps and motors. Consequently, the real growth of wind energy as an electric power source began, and it moved forward step by step [7]. Vantikanten blades were enforced by Kurt Bilau in 1920 to create a new windmill [8]. During 1920–1930s, the windmill recognition rose and reached its highest peak through the closing stages of this era using more than 600,000 wind turbine units installed in farms and rural areas in the United States. Generally of those wind machines were alone capable of generating less than 1 kW of electrical energy [9]. Wind market started to sluggish downwards next to the end of 1950 with the advance in power lines construction tools, except earlier that, various farms were using wind-generated electrical energy using the latest existing technology of horizontal axis wind turbine, that built-in 1941 [10]. By focusing on the wind power market, it apparently might be stated that this market and a chronicle of wind energy improvement linked to fossil fuel price [11]. Wind power service accomplished a significant increase for the previous decade. Wind power production doubles in every 3.5 years since the establishment of the 21st century [12, 13].

1.3 Wind energy as a future energy

The wind energy average growth rate of 30%, is the fastest growing source of renewable power on the planet. India occupies the fifth position in the world in wind energy generation after USA, Germany, Spain, and China and has an installed capacity of more than 9756 MW as of January 31, 2009[14]. However, the pictorial representation of 450 KW and 1.5 MW wind turbines are shown in Figure (1.1) which is given below.

450 KW WIND TURBINE 1.5 MW WIND TURBINES

Figure 1.1: wind turbines

The Indian renewable energy zone has demonstrated impressive growth over the past few years, and investments in the industry have enlarged considerably. The distribute of renewable energy was 7.7% in the cumulative installed capacity of electric power plants beneath utilities in India until December 2008. The Indian government by 2012 anticipates renewable energy to donate 10% of the total power production capability and have 4%–5% share in the electricity mix[15]. The Integrated Energy Policy Report of the Planning Commission of India has experiential that the contribute to of current renewable to India's energy mix by 2031–2032, excluding large hydro, would be approximately 5%–6% [16]. Every year, more technological advancements are announced, however, that increase efficiency and decrease cost. The Schematic Diagram for Variable-speed Wind Turbine is shown in [17] Figure (1.2) as follows;

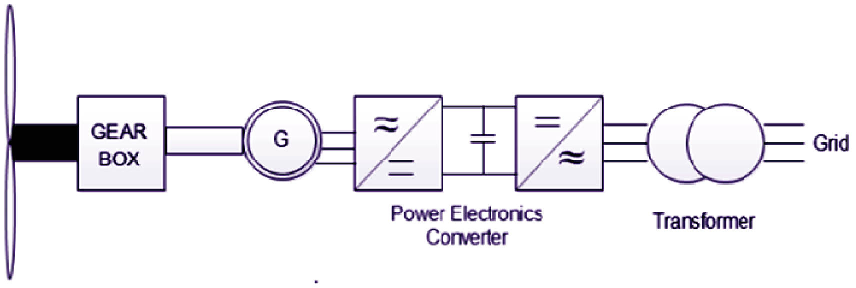
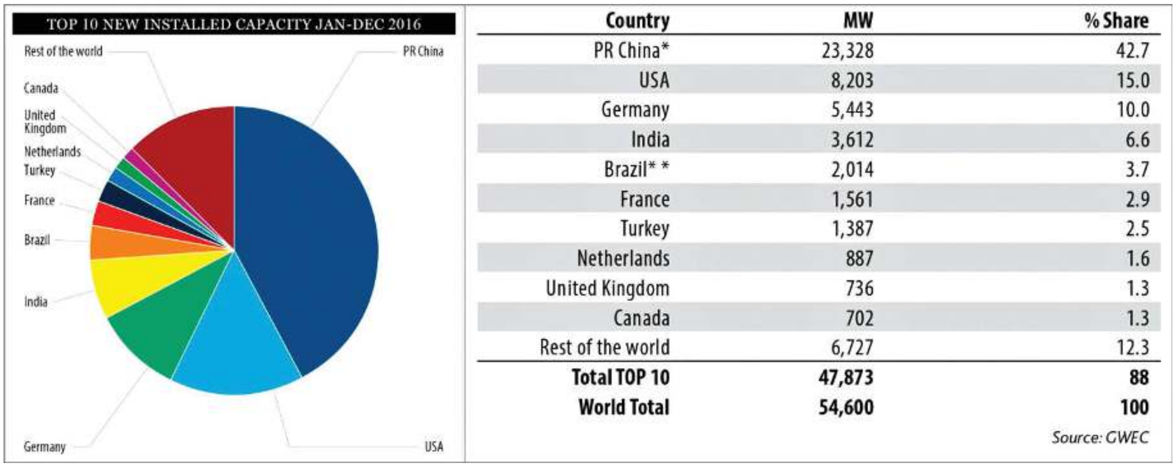


Figure 1.2: Schematic Diagram for Variable-speed Wind Turbine

1.4 Statistics of wind energy

With the quickly increasing demand intended for power along with an importance on clean energy, India has also taken its step forward along with other countries. According to the Global Wind Report 2016, the total installed wind capacity at the end of 2016 is just shy of 486 GW. Out of the whole size, India installed wind power generation capacity stood at about 28,700 MW constitute 5.9% of global wind power capacity as shown[18] in Figure (1.3).

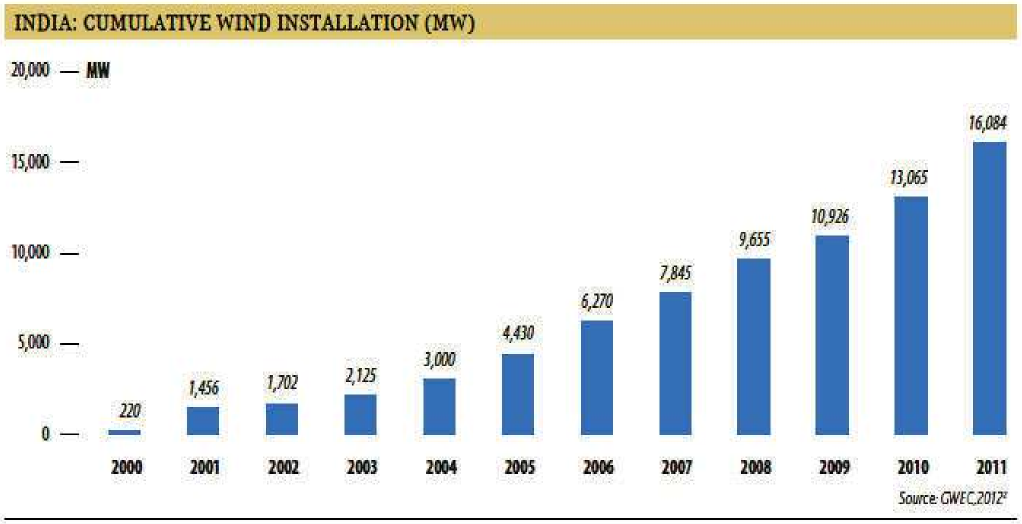


Country	MW	% Share
PR China*	23,328	42.7
USA	8,203	15.0
Germany	5,443	10.0
India	3,612	6.6
Brazil* *	2,014	3.7
France	1,561	2.9
Turkey	1,387	2.5
Netherlands	887	1.6
United Kingdom	736	1.3
Canada	702	1.3
Rest of the world	6,727	12.3
Total TOP 10	**47,873**	**88**
World Total	**54,600**	**100**

Source: GWEC

Figure1.3: Statistical data of Global cumulative wind capacity

Wind Energy- Indian Scenario: In the early 1980s, the government of India demonstrated the Ministry of Non-Conventional Energy Sources (MNES) to push diversification of the country's energy supply as well as meet the ever-increasing energy demand of its quickly growing economy. In 2006, this ministry was renamed as the Ministry of New and Renewable Energy (MNRE). For the first decade of the 21st century; India emerged as the 2nd leading wind power market in Asia. More than 2,100 MW wind capacity thesis were added in the financial year 2010–11. The installed capacity increased from a modest base of 41.3 MW in 1992 to reach 28,700 MW by December 2016. India had an additional documentation year of different wind energy installation stuck between January as well as December 2011, installing extra than 3 GW of different capacity for the first time to reach a total of 16,084 MW shown[19] in Figure(1.4). As for March 2012, renewable energy accounted for 12.2 percent of total established capacity, up to from 2 percent in 1995. Wind power explains about 70 percent of this installed capacity. By the end of August 2012, wind power installations in India had reached 17.9 GW.



Source: GWEC,2012²

Figure1.4: Statistical data of India's wind energy mechanism

Modern wind power technology has come a long way in the last two decades, both globally and India. Enhanced technology has slowly and steadily improved capability efficiency. An essential drift in the Indian industry which is the expansion of multi-megawatt turbines established at larger hub heights. Larger diameter rotors allow a single wind power generator to capture more energy or power per tower. That allows WTGs to take advantage of higher altitudes with stronger winds and less turbulence (wind speed enhance with height above the earth). The larger machines had resulted in a solid improvement in the capacity factor on the standard as of 10-12% in 1998 to 20-22% in 2010. Intended for two decades, nowadays, worldwide standard WTG power ratings have developed approximately, with modern industrial machines rated on normal in the range of 1.5 MW to 2.1 MW.

1.5 Wind Energy Conversion System

The global cumulative wind power capacity worldwide has shown [20] in Figure (1.5).

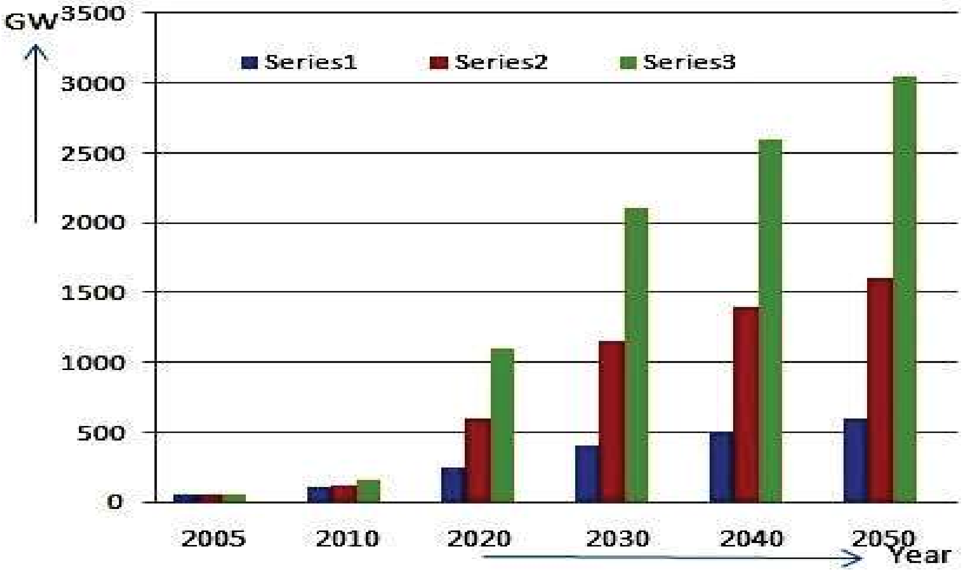


Figure 1.5 Global cumulative wind power capacities

Here in figure (1.5), the ‘Reference’ position is based on the outcrop in the 2004 World Energy Outlook report from the IEA [20], and also in this projects the development of all renewable including wind power, till now 2050 has been described. According to trends in world and obligations forced on European countries to generate a portion of electrical energy from renewable sources [20]. The connection of the wind turbine to the grid is promising at different levels of voltage are described in [21]. Power electronics converters also raised energy extraction and variable speed operation of the wind turbine. Figure (1.6) presents the topology of a total wind energy conversion system [21].

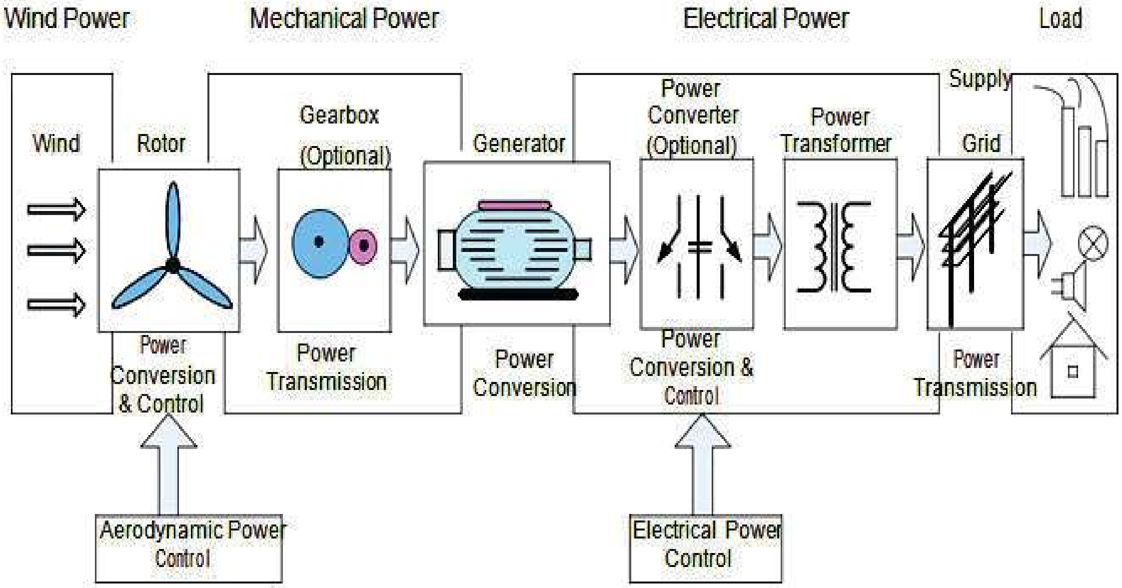


Figure 1.6 Wind Energy Conversion Systems

However, the general equation governing the mechanical power output of the wind turbine is given by [22].

$$P_m = \frac{1}{2}\rho A_r v^3 C_p(\lambda, \beta) \tag{1}$$

Where,

P_m= mechanical power extracted from turbine rotor,

ρ = air density [kg/m^3],

A_r= area covered by the turbine blade; πR^2; R being the radius of turbine blade in meters (m),

C_p= Power coefficient or performance coefficient,

β = Pitch angle,

λ = Tip speed ratio $\simeq R\omega_r/v$;

ω_r= Turbine rotation speed,

v = Wind velocity.

The power output from the turbine as given by the power equation depends on factors like the radius of the turbine blade, wind velocity, and power coefficient.

1.6 Type of Generators used in wind turbine for WECs

The choice of generator type in wind turbines is based on cost, efficiency, and the ability to power generate under conditions of varying wind speed [23]. Every kind of wind turbine has its dominant performance, and their relevant, innovative researchers on wind energy are not stopped today; meanwhile, power output varies with wind speed. Nowadays, induction and synchronous machines account for the most significant share of the market in a generator for wind energy applications, due to their inherent advantages and disadvantages of characteristics and market background [24]. Direct current generators were adopted when wind energy technology started to be developed, but in recent years these are rarely seen due to their limitations. Beside this, switched reluctance machine is attempting to be applied in the wind energy application [25].

1.6.1 Direct Current Generator

Direct current (DC) generators were a historically significant type of electrical machine for wind energy applications [26]. In the past, it was used in small-sized, battery charging wind turbines. The conventional DC generator has the same essential elements as the alternating current (AC) generator so that when current pass through the field winding, an electric field is generated.

Beside this, a commutator is installed on the rotor to rectify the power to DC. Meanwhile, brushes are needed to transmit the generated current. A characteristic of DC generator is that the magnetic field, armature voltage, and electrical torque increase with speed. However, DC generators are rarely used today, due to their high costs and maintenance requirements. And they are to work in large power systems; the fire hazards of wiring must be solved [25].

1.6.2 Permanent Magnet Synchronous Generator

The Permanent Magnet Synchronous Generator (PMSG) is applied more frequently in both large and small wind turbine applications today [25]. Because PMSG has higher efficiency compared with another machine type, on the other hand, it is operating in the constant torque region, along with high torque density due to their lightweight and straightforward rotor structure without windings. Therefore, its right performance makes the PMSG likely to be an excellent choice in the future with the development of rare-earth magnets. Meanwhile, a particular design needs to be used in wind energy, which is the direct drive PMSG. It is because the direct-drive wind energy system is not able to adopt the conventional high-speed electrical machines. This kind of generator has a sufficient number of poles to enable the generator rotor to turn at the similar speed as the wind turbine rotor, and so the gearbox is no longer needed. Direct drive generators on wind turbines are used with power electronic converters. Due to a large number of poles, the size of the generators is relatively large, so it is quite essential for machine designers to minimize their size and weight with high torque density. Besides, Neodymium as the most relevant material in permanent magnet machines, and therefore cost-effectiveness is another critical issue which must be considered carefully [27]. On the other hand, the PMGs are classified in [23] as follows;

(i) Radial Flux Machine

(ii) Axial Flux Machine

(iii) Transverse Flux Machine

1.6.3 The switched reluctance generator (SRG)

The switched reluctance generator (SRG) is proposed as a useful option for machines in the future for wind energy applications [26]. No SRGs are currently installed in wind turbines, but research in this direction is underway. The SRG is suitable for any high-speed use due to its simple, robust iron rotor without any windings or magnets. Meanwhile, the cost of an SRG is quite cheap, because there is only iron and copper in the structure; however, due to the need to have a small air-gap, the manufacturing tolerances can be tight. Because of its simple construction, the SRG does not need much maintenance. At present, the development of the SRG is matched with using of power electronic converters. However, the advantages of the SRG are also drawbacks in some ways. For example, the iron loss of its rotor can be significantly higher than with other machine technologies at high speed, and moreover, these machines generate loud acoustic noise, and the torque ripple is very high due to its operational mode. At present no turbine manufactures build SRGs [28].

1.6.4 Induction Generator

Among all of the main types of generator used for wind energy applications, the induction generators are the most commonly used [29]. They are asynchronous generators, and so they can operate at variable speeds, which is suitable for wind power generation due to the full range of wind speeds involved. Furthermore, their simple, rugged construction, relatively low cost, and ease of manufacture are also primary reasons for them to be adopted in industrial applications in recent years. The induction machine is very efficient in the constant power region, where a small magnetization current is required, and also the continual power region can easily be extended to

4-5 times the base speed. However, the drawback of the induction machine is a lower torque density, and their efficiency is more economical when operating at lower rates. Induction machines also require an external source of reactive power, along with an external constant frequency source to control the speed (n_s) of rotation [26].

$$n_s = \frac{120f}{p} \tag{2}$$

Where the supply frequency is in Hertz and p is the number of magnetic pole pairs. However, Slip is the percentage of the difference between the synchronous speed n_s and the rotor speed n_r at the same frequency

$$S = \frac{n_s - n_r}{n_s} \tag{3}$$

For motor operation, the slip is positive; and for generator operation, the slip is negative. Currently, there are two main types of induction generator which are used in wind turbines. These are the squirrel cage induction generator and the wound rotor induction generator respectively [30].

1.6.4.1 Squirrel Cage Induction Generator

The SCIG has solid conducting bars embedded in the grooves, and both side ends are shorted through end rings so that the bar structure make the rotor look like a squirrel cage, as shown in Figure (1.7) [29]. The conducting bars are composed of stacks of electrical steel laminations, which are made of either copper or aluminum. The stator structure of this kind of generator is similar to that of a synchronous generator. The solid conducting bars usually adopt a slightly skewed design which can eliminate torque ripple and reduce noise [26].

Figure1.7: Squirrel cage induction machine

In wind energy applications, the SCIG is coupled with the grid directly through a drive train system, which enables stall-regulated machines to operate at constant speed. These are defined as the singly fed induction generator (SFIG). The simple, rugged and cost-effective construction of the SFIG has the interest of attracted wind turbine manufacturer. But the reactive power must be consumed in the SFIG because of its magnetizing reactance, and this is undesirable especially in giant wind turbines and weak grids [27]. Therefore, a compensating capacitor is adapted to compensate for the reactive power consumption, as shown in Figure (1.8). So the SFIG is usually used in low power installations (<1MW per Turbine),

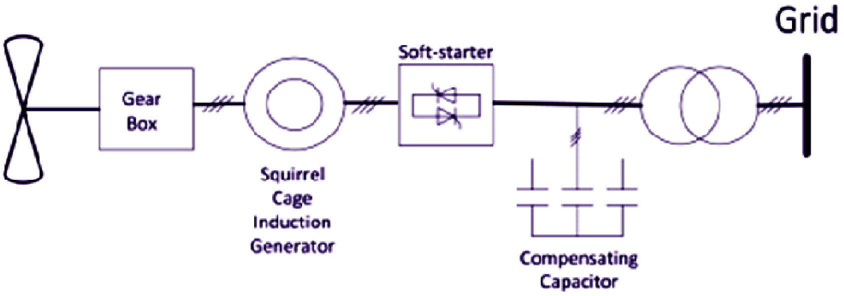


Figure1.8: A single fed induction generator scheme

The drawback of the SFIG is that the speed of the machine is uncontrollable and variable only in a very narrow range. Furthermore, generator operation is only available when the running speed is higher than the synchronous speed. It is well known that wind speed is variable and irregular, so this type of wind turbine is not able to adjust to change speed, which causes low efficiency. The difficulties of gearbox maintenance and acoustical noise are additional problems with the SFIG [25].An advanced version of the SCIG uses a back-to-back power converter to instead of the capacitor bank. So a gearbox is still used, and the generator is connected to the grid, through a back-to-back power converter. This is termed a fully rated converter SFIG as shown in Figure (1.9). With this design, the ability to capture energy is better than with the conventional design, but the cost of a full-scale back-to-back power converter should be considered carefully due to its full power rating [29].

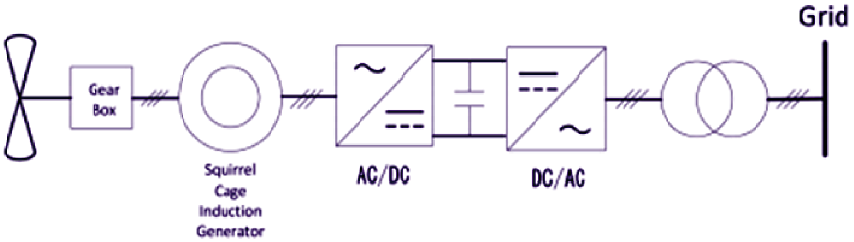


Figure 1.9: An advanced single fed induction generator scheme

1.6.4.2 Wound Rotor Induction Generator: The Wound Rotor Induction Generator (WRIG) has the same stator structure as the squirrel cage generator, but the rotor structure is entirely different in that the insulated windings are placed in the rotor slots, and the rotor is brought out via slip rings and brushes. The rotor component is punched by stacked laminations and fitted directly onto the shaft. In wind turbine applications, the WRIG adopts variable resistance and a compensating capacitor in the system. Its stator is connected to the grid directly, while the rotor is connected to a variable resistance, as shown in Figure (1.10). In that case, variable speed operation can be achieved by controlling the energy extracted from the WRIG rotor, but this power must be dissipated in the external resistor [29].

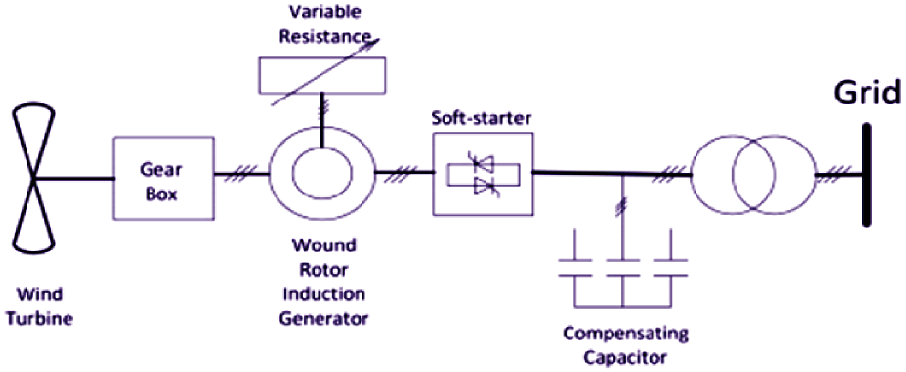


Figure 1.10: Schematic of a wound rotor induction generator

1.6.5 Doubly Fed Induction Generator

The Doubly Fed Induction Generator (DFIG) is constructed from a WRIG with multiphase windings which feed AC currents into both stator and rotor windings, where the former is connected to the grid directly [31]. In the rotor, the winding is connected to a multiphase slip ring assembly with brushes which are used to transfer the power, to achieve the energy conversion with the grid typically via a bi-directional back-to-back voltage source converter. This part of the power in the rotor is the slip power, which could be either fed from the grid or delivered to the network. The back-to-back converter consists of three components: a rotor side converter (RSC), DC link capacitor, and grid side converter (GSC). Inside the back-to-back converter, the rotor side converter is used to control the speed or torque of the DFIG and the machine power factor; the role of grid side converter is to minimize the DC link capacitor's voltage ripple. Figure (1.11) demonstrates a schematic diagram of DFIG-based wind turbine system. The DFIG has become popular in recent years, and now is one of the most attractive wind turbines for industrial applications, especially large-scale turbines [29].

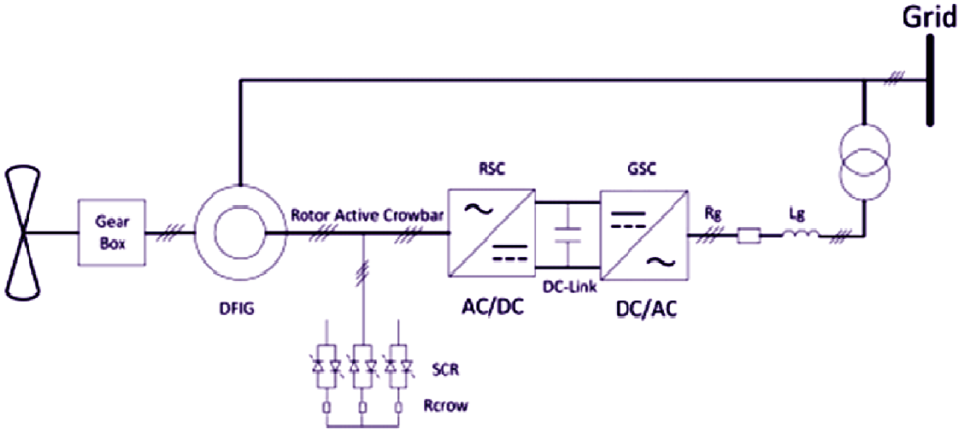


Figure 1.11: Schematic of a doubly fed induction generator for wind turbine system

In variable speed wind turbines, as the name suggests, the rotation speed of the generators could vary with wind speed. However, the three-phase asynchronous generator cannot be used in variable speed wind turbines, because it is connected to the grid directly with a nearly fixed rotation speed, which is similar to the synchronous generators. With wind speed fluctuating naturally, both the torque and the power output of the wind turbines will change together accordingly, and if a sudden wind gust occurs, the torque of the generator increases significantly, as does the power output of the wind turbine. It is well known that significant fluctuations in power output from wind turbines can cause the destabilization of the grid [27]. DFIGs are used since they can produce constant voltage and frequency outputs by adjusting the amplitude and frequency of the AC fed into the generator rotor winding, whatever the variation of either generator rotation speed or wind speed. Hence, the primary feature of the DFIG is that it can connect to the grid directly as an asynchronous generator and to remain synchronized with the AC power grid in the meantime. When the grid fault or an abrupt voltage drop occurs, the ability of low voltage ride through could keep wind energy conversion system remain connected to the grid and provide ancillary services. Moreover, according to the same method, regulation of the amount of reactive power exchanged between the generator and the power grid could control the power factor of the system. So the DFIG can operate close to a power factor of unity [29]. The DFIG's rotor is associated to the grid via a power electronic converter, which means that the rotor part actively participates in energy conversion with the power grid. So the converter in the DFIG only needs to carry part of the power output, which is typically 30% of the rated power output in industrial applications today. Accordingly, the size of the power electronic converter used in DFIG is approximately only 30% of those employed in synchronous generators for variable speed wind turbines. Consequently, the cost and losses of power electronic converters in DFIG are reduced to achieve the same variable speed control compared with synchronous generators [28].

1.7 Types of Wind Energy Conversion Systems

The speed control norm leads to two types of WECS: Fixed speed and Variable-speed [21][32][33].

1.7.1 Permanent Speed WECS

Fixed or permanent-speed WECS are electrically simple devices, containing an aerodynamic rotor driving a SCIG or a WRIG which directly associated with gearbox and shaft. The rotor speed (about 1-2%) is determined by the frequency of the supply grid, the gear ratio and the number of pole-pairs of a generator, in spite of the wind speed. For compensation of reactive power, capacitors have used. Very commonly a squirrel cage induction motor with a selected number of poles, generally for two different speeds as shown in Figure (1.12) is used [32].

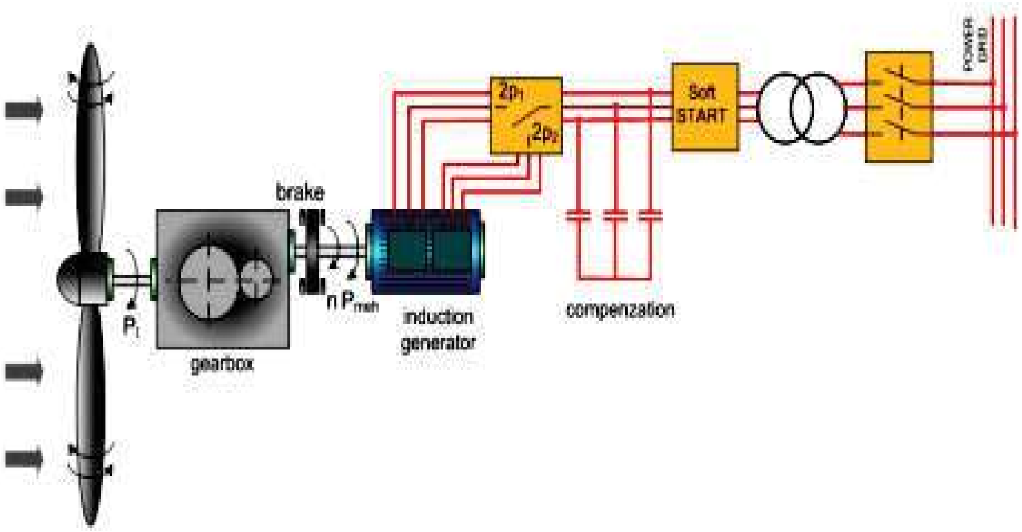


Figure 1.12: Fixed speed WECS

1.7.2 Variable Speed WECS

The most significant advantages of variable-speed WECS increased power to capture, enhanced system efficiency, improved power quality by fewer flickers, substantial mechanical stress, reduced fatigue, and reduced acoustic noise. Both conventional synchronous generator and the conception of DFIG utilized for variable speed WECS. DFIG comprises of a WRIG with the stator windings instantly associated with the constant frequency three phase grids and with the rotor windings mounted to a bi-directional serial IGBT voltage source converter. Full-term 'doubly fed' concerns to the fact to the voltage on the stator are enforced from grid along with voltage on the rotor are induced by the power converter [34]. The construction shown in Figure(1.14) is more favorable than Figure(1.13) due to smaller size and price of the power converter, poorer harmonic subject matter in the electricity grid generated by the converter, improved controllability, lesser essential gap, and enhanced stability of the power system along with the possibility to generate reactive power. The Variable-speed WECS with the synchronous machine shown in Figure (1.13), [21]; whereas Figure (1.14) shows Variable-speed WECS with DFIG [33].

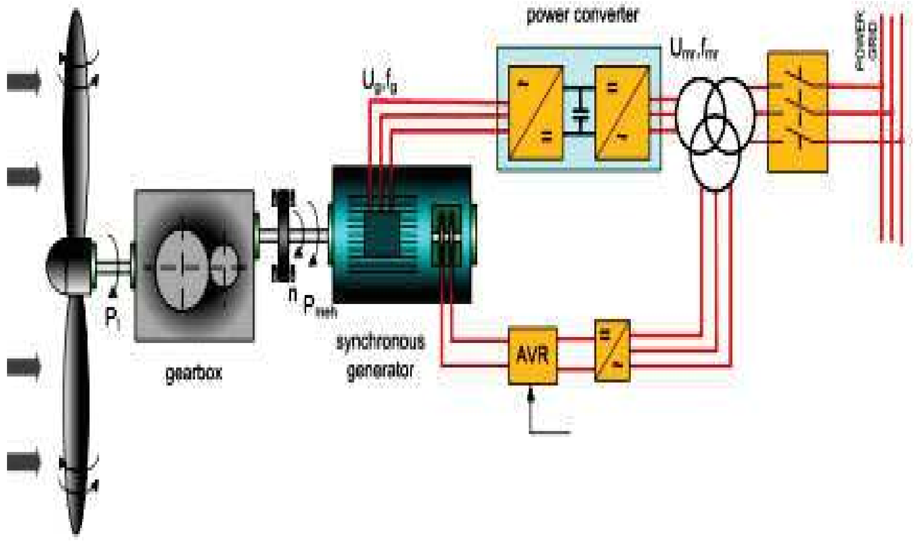


Figure1.13: Variable-speed WECS with synchronous machine

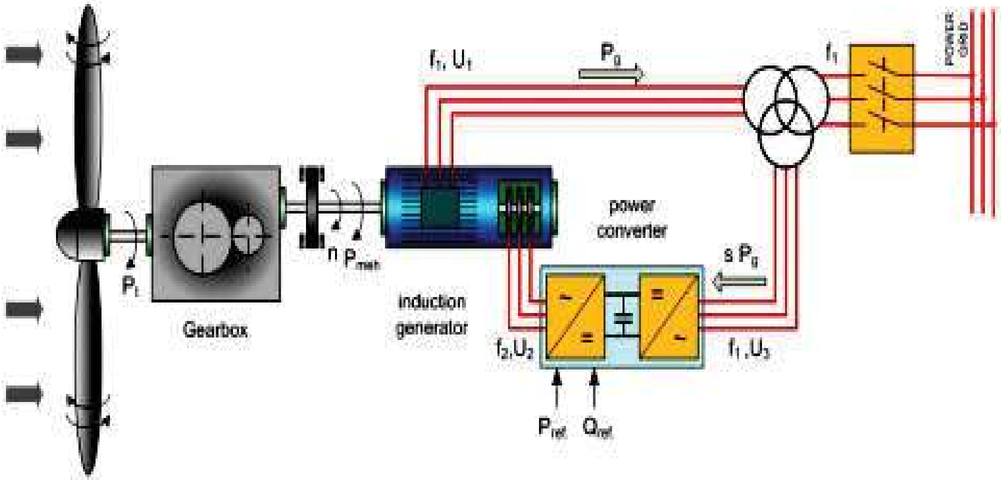


Figure 1.14: Variable-speed WECS with DFIG

The advantages and disadvantages of WECS generators detailed given in [20, 21, 32, 33] as Table (1.1).

Table1.1 Benefits and drawbacks of WECS generators details

Type	Advantages	Disadvantages
Induction Generator	(i) Full speed range (ii) No brushes (iii)Active and reactive power control (iv) Proven technology	(i)Full-scale power converter (ii) Need gearbox
Synchronous Generator	(i) Full speed range (ii) Possible to avoid gearbox (iii)Active and reactive power control	(i)Small converter for field (ii)Full scale power converter
Permanent Magnet Synchronous Generator	(i) Full speed range (ii) Brushless (iii) No power converter for field (iv) Possible to avoid gearbox (v)Active and reactive power control	(i)Full-scale power converter (ii) Multiple generator (iii)Permanent magnets High cost (iv)Demagnetization possibility
Doubly Fed Induction Generator	(i)Sub-synchronous and super synchronous operation is possible (ii)Inexpensive PWM inverter (iii) Active and reactive power control	(i) Need slip rings (ii) Direct connect to grid is Somewhat difficult (iii) Need gearbox

1.8 DFIG Necessities

In current years more consideration has been given to induction machinery since they are used for low and medium power application. Gorgeous advantages over conventional generators are lower unit cost, less maintenance, and robust construction, etc. [26]. Doubly-Fed Induction generator (DFIG) is particularly suitable for a remote operation like hydro and wind developments. DFIGs are presently dominating the renewable energy market. Over the last decades, DFIG-based wind turbines have been most preferred option for high capacity wind farms because it can control the active and reactive power exchange within the network [28]. DFIGs can operate constant speed region to attain a smoothened and double the power than any other conventional generator produces. The growth of wind turbine techniques, DFIG is becoming more popular because of its unique characteristics such as high efficiency, low cost, and flexible control. Doubly fed induction machines succeed to all the compensation of a cage induction generator. But the fact due to which more popular than the stator of the DFIG is linked in a straight line to the network and supply power from the stator side at grid voltage and frequency. The power converters used for DFIG control, which decreases the cost as well as the switch losses that result in improved efficiency. There are regularly two modes for the DFIG variable-speed wind turbines which are cross-coupled to each other [28]. The first way in low wind speed below-rated value and speed controller can continuously regulate the speed of the rotor. To uphold the tip speed ratio constant at the level which provides the maximum power coefficient and the efficiency of the turbine will be extensively improved. The generator is controlled by power electronic equipment to control the rotor speed. However for the second mode, in high wind speed above rated value, pitch angle regulation is necessary for the situation above the rated wind speed where the rotational speed is kept constant.

Advantages of DFIG over other wind generators [28]

- Operates under conditions in which both rotor and wind speeds are variable while the amplitude and frequency of output voltage remain constant.
- Ability to control the power factor.

- The price of the converter is lower than full rated power converter, due to it carrying a power rating of about 30% of the system power output.
- It Performs well with excellent efficiency to another generator.

Drawbacks of the DFIG with a gearbox [28]

- Maintenance of slip rings and gearbox required.
- Limited capacity to supply reactive power.
- High torque occurs during fault conditions, which require the ability of low voltage ride through.
- Start-up current shall be limited via the voltage source converters.

To eliminate the maintenance requirements of the slip rings, a brushless DFIG has been developed. Here, a multiphase slip ring assembly is no longer needed, but there are still a lot of problems with the efficiency, cost, and size of the brushless DFIG. Despite this, the DFIG is always by far the leading choice to be used in wind turbines to produce electricity.

1.9 A general idea of the DFIG

A part of wound rotor induction generators, also known as the (DFIG), is one of the most frequently used generators in the wind energy industries [35]. Currently, these types of generators are extensively accepted as one of the appropriate wind energy conversion systems. As depicted in Figure (1.15), [36].

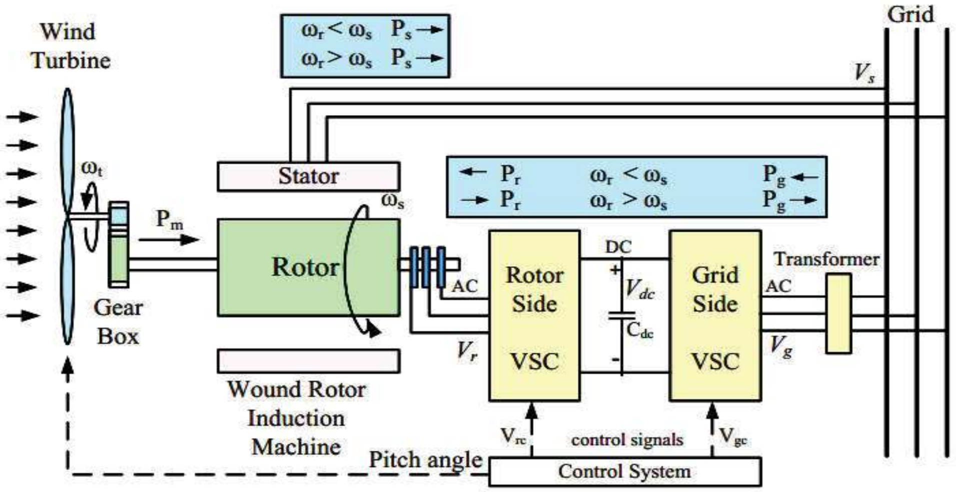


Figure1.15: Doubly fed induction generator typical installation diagram as a wind generator

The DFIG is fundamentally a wound rotor induction generator, and electric power devices usually control their rotor circuit, for variable speed function. Whereas the DFIG stator winding associated directly to the grid by a power transformer and DFIG's power is ranged from a few kilowatts to many megawatts. A rotor converter size is nearly 30% of a full capability converter. For the duration of low wind speed, additional electrical energy could be acquired from a variable speed DFIG, an individual with a fixed speed wind generator [37]. Finally, the profit of using DFIG in WECS is described in [38]. Whereas in [39] DFIGs have two operating modes; in (i) mode $\omega_r > \omega_s$, S; is –ve. The generator in super-synchronous mode and both stators, as well as rotor windings, deliver power to the grid. While in (ii) mode $\omega_r < \omega_s$, S is +ve the generator in sub-synchronous mode and stator winding provides power to in cooperation the grid and the rotor winding.

The DFIG exchanges power with the grid when operating in either sub or super synchronous speeds. These operating modes are analyzed as follows [40].

1.9.1 DFIG operating modes

The DFIG stator is associated to the grid through fixed grid frequency (f_s) at permanent grid voltage (V_s) to generate the constant rate. The rotor is related to frequency converter/VSC having a changeable (slip/rotor) frequency ($f_r= s \,.\, f_s$), at constant frequency f_s. Whereas magnetic field produced in the stator, that rotates at constant angular velocity/speed ($\omega s= 2\ \pi$ fs) called the synchronous speed of the machine. The stator rotating magnetic field will bring a voltage between the terminals of the rotor. The induced rotor voltage develops a rotor current (I_r), which produce a rotor magnetic field that rotates at variable angular velocity/speed ($\omega_r = 2\ \pi\, f_r$). Stator and rotor have the same number of poles (P), and the convention is that stator magnetic field rotates clockwise. Hence stator magnetic field rotates clockwise at a fixed constant speed such as; $\omega_s\ (rpm) = 120\, f_s / P$. Since the rotor is associated with variable frequency VSC, the rotor magnetic field rotates at a speed of $\omega_r\ (rpm) = 120\, f_r / P$

Sub-synchronous speed mode: Figure (1.16) illustrates the case where the rotor magnetic field rotates at a slower speed than the stator magnetic field.

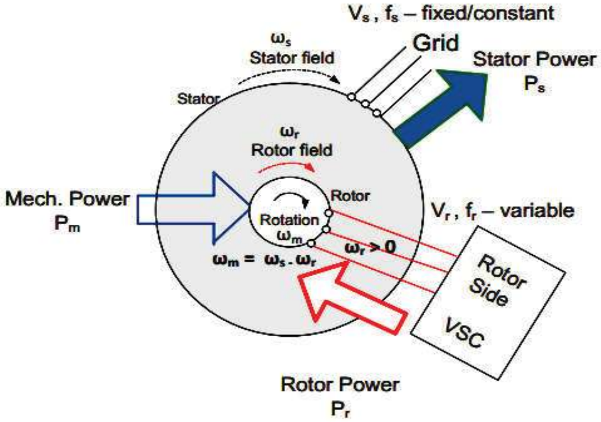


Figure 1.16: Sub-synchronous operating mode of DFIG

The machine is worked in the sub-synchronous mode, i.e., $\omega_m<\omega_s$; If and only if its speed is exactly $\omega_m= \omega_s-\omega_r>0$. And the phase sequences of the rotor along with stator MMF's are the same, in a positive direction, as a concerned to as positive phase sequence ($\omega_r > 0$). For maximum power extraction following conditions should be satisfied:

- The rotor side VSC shall provide low-frequency AC (negative V_r will apply) for rotor winding.
- The rotor power will be provided using a DC bus capacitor through the rotor side VSC, which tends to reduce the DC bus voltage.
- The grid side VSC increases/controls this DC voltage as well as manages to remain it constant. Power is engrossed as of the grid using the grid side VSC as well as delivered to the rotor through the rotor side VSC. For the duration of this working mode, the network side VSC operates as a rectifier as well as rotor side VSC functions as an inverter. This power is delivered to the grid by the stator along with rotor is capacitive.

Super-synchronous speed mode: It is achieved by having the rotor magnetic field rotate counterclockwise. Figure (1.17) represents this scenario. However, to represent the counterclockwise rotation of the rotor, which is analytically equivalent to inverting the direction of the rotor magnetic field.

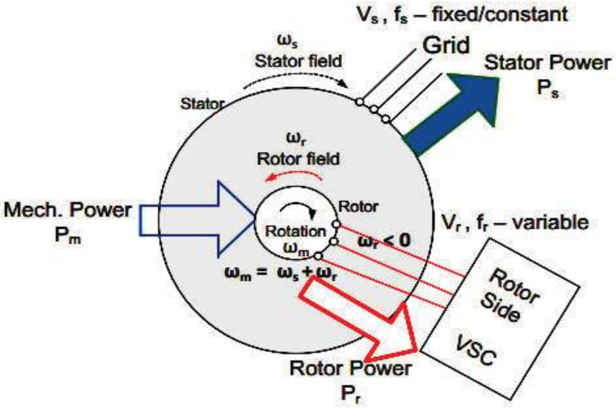


Figure 1.17: Super-Synchronous operating mode of DFIG

The machine is functioned in super-synchronous mode, i.e., $\omega m>\omega s$, if and only if its speed is closely $\omega m=\omega s-(-\omega r) = \omega s+\omega r>0$. The phase sequence in the rotor rotates in the opposite direction to that of the stator, i.e., negative phase sequence ($\omega r<0$). This situation takes place during the condition of high wind speeds. The following circumstances need to be fulfilled to extract maximum power from the wind turbine as well as to reduce mechanical stress:

- The rotor winding delivers the AC power to the grid through the VSC. The rotor power is transmitted to DC bus capacitor, which tends to raise the DC voltage.
- The grid side VSC reduces the DC-link voltage and manages to keep it constant. Power is extracted from the rotor side VSC and delivered to the network.
- Hence power is delivered to the grid straightforwardly by the stator along with VSC via the rotor.The rotor power is inductive.

Synchronous speed mode: The synchronous speed mode is presented in Figure (1.18).

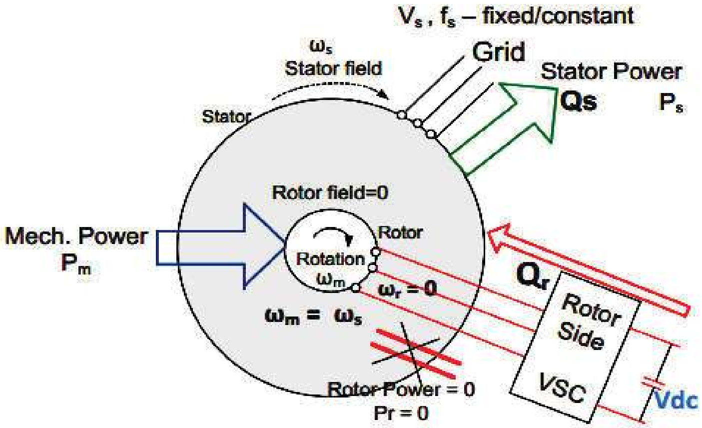


Figure 1.18: Synchronous operating mode of DFIG

The machine is operated in the synchronous mode, i.e., $\omega_m = \omega_s$, if and only if its speed is closely $\omega_m = \omega_s - 0 = \omega_s>0$. The phase sequence in the rotor is the same as that of the stator, but no rotor

MMF is produced (ω_r =0).The following conditions are necessary to take out maximum power from the wind turbine as follows:

- Rotor side converter affords DC excitation for the rotor by which generator operates as a synchronous machine.
- Rotor side VSC will not provide any AC/power for the rotor winding. Hence the rotor power is zero ($P_r = 0$). The considerable amount of reactive power will be supplied to the grid using the stator.
- As per the operating modes; which is described above, at any wind speeds a broad variety of variable speed operation can be performed to achieve maximum wind power extraction.

1.10 Power stream features of DFIG

For a conventional wound rotor induction machine, the rotor windings are shorted at the slip rings so that there is no power outputted from the rotor except rotor loss only. For a DFIG, however, to obtain sub- and super- synchronous speed operation, the converter has to be able to hold slip power in both directions [40] and therefore both real and reactive power P, and Q could be conveyed in either direction at grid frequency. When the power loss is ignored, the real power and reactive power can be expressed as.

$$P_m = T_m \omega_r \tag{4}$$

$$P_s = T_e \omega_s \tag{5}$$

$$J \frac{d\omega_r}{dt} + B\omega_r = T_m - T_e \tag{6}$$

Here J is inertia coefficient, and B represents friction. At the steady-state for the lossless generator, when the conflict is ignored (B=0).

$$T_m = T_e \tag{7}$$

$$P_r = P_m - P_s = T_m\omega_r - T_e\omega_s = -T_m\left(\frac{\omega_s - \omega_r}{\omega_s}\right)\omega_s = -s_1 T_m\omega_s = -s_1 P_s \tag{8}$$

$$P_m = \left(1 - s_1\right) P_s \tag{9}$$

$$Q_{sr} = Q_s + \frac{Q_r}{s_1} \tag{10}$$

$$P_{grid} \approx P_s + P_r \tag{11}$$

On the one hand, when slip is 0 at synchronous speed, the power only transfers between the stator and mechanical shaft, while at a stationary state whose slip is 1 and mechanical rotor frequency is 0, the power flow only takes place in the stator and the rotor. Besides, depending on the DFIG operating in sub- or super- synchronous modes, the mechanical shaft would feed energy to the stator, and the real stator power P_s is always flowing from the stator to the grid, whereas the rotor power P_r would change the direction at different modes. As Figure (1.19) illustrates, power flow conveys towards the grid and increases linearly when the slip is negative at over-synchronous speed, while reverses to the rotor at the sub-synchronous with positive slip and reduces linearly with the rise of mechanical power P_m. The real power delivered to the rotor at sub-synchronous speed depends primarily on the amplitude of the voltage injected into the rotor and the peak rotor power absorbed from the converter occurs around the synchronous speed. At that time, the slip is near zero, and the rotor is close to a short circuit. In other words, to prevent such high peak rotor power or current, the DFIG should not be operated near synchronous speed.

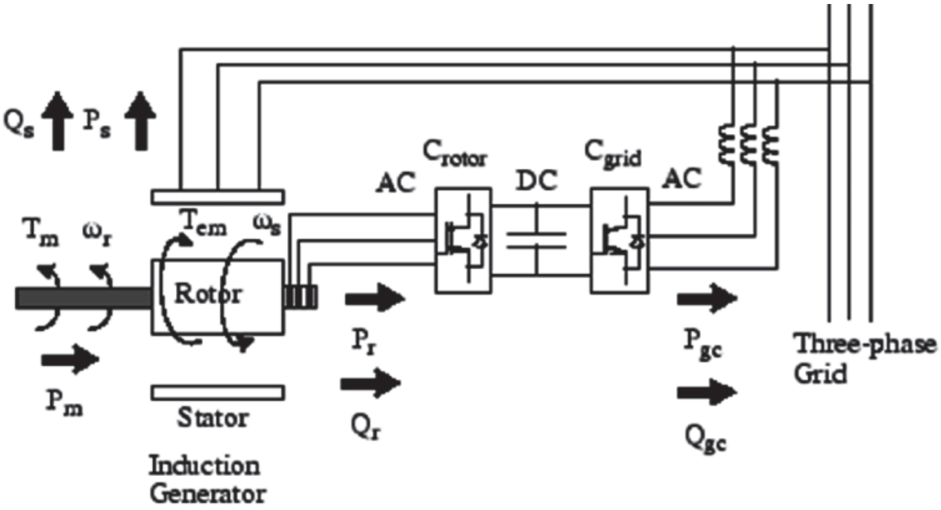


Figure 1.19: Power flow diagram of DFIG

On the other hand, the rotor reactive power Q_r and Q_g should be adjusted by the controller to make sure that the reactive grid power Q_{grid} is zero and to reduce the reactive power Q_r transmitted between the rotor and the converter. Although the reactive power Q_r is not conveyed to the network through the grid-side converter under the constant DC-link voltage condition, it may cause overall rotor power to exceed the power ratings of the rotor-side converter and therefore influence the practical DFIG control objectives [41]. Additionally, the DFIG equivalent circuit with apparent resistance and torque-speed characteristics of DFIG above and below the synchronous speed has been described in [19,41] as shown in Figure (1.20,1.21&1.22) given below.

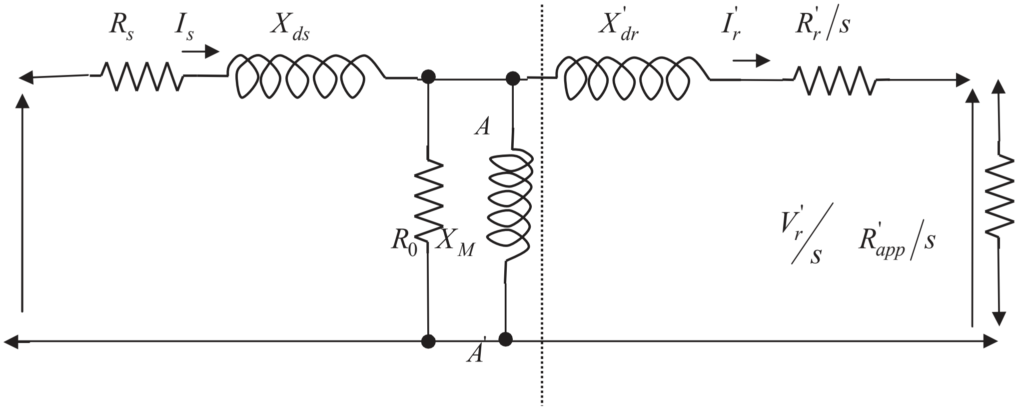


Figure 1.20: DFIG equivalent circuit with apparent resistance

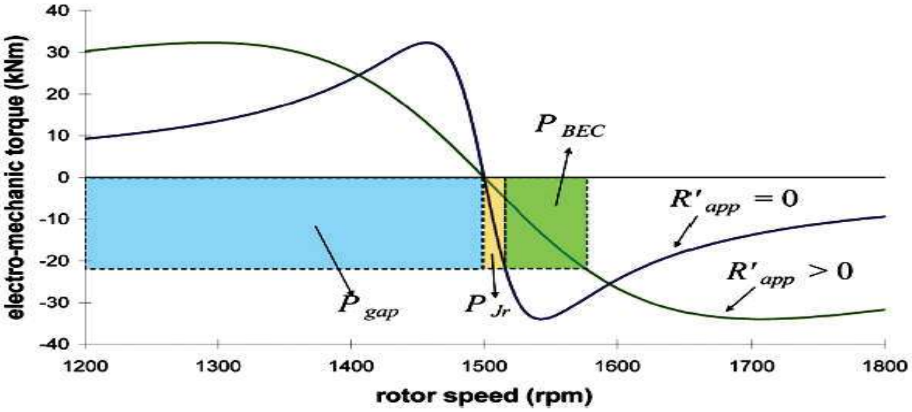


Figure 1.21: Torque-speed characteristics of DFIG above the synchronous speed

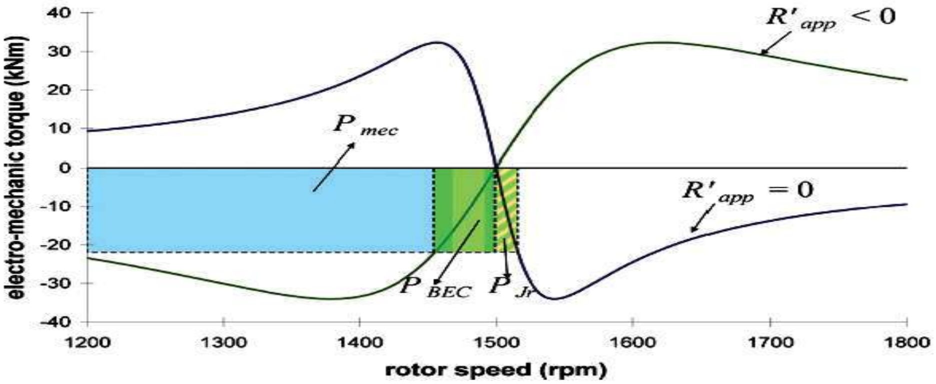


Figure 1.22: Torque-speed characteristics of DFIG below the synchronous speed

1.11 Review of Related Research

The investigation of progressively alternate energy sources, demand for electric energy is increasing very fast. Among the available alternative energy sources, wind energy, solar energy, and fuel cells have drawn considerable attention. Additional, all of these alternate energy sources are also of renewable nature. Among the mentioned alternate energy sources, wind power generation systems have been most cost competitive alternative among all the environmentally clean and safe renewable energy sources in the world. Due to stochastic nature of wind, the variable speed wind turbine technology offers inherent advantages over the fixed speed one [1]. The doubly fed induction generator (DFIG) is used in sequence with the wind turbine to produce electric energy. The DFIG using the two back to back converters: rotor side and grid side converters can deal with the variation of wind speed with a limited range ±30% around the synchronous speed by injecting a compensating variable frequency current component in the rotor circuit. This facilitates both super and sub-synchronous operations of DFIG. It is well known that the induction machine is widely used in industrial application due to its low cost, the simplicity of construction and low maintenance cost. Such type of machines can be used for an electric generation where the speed of the prime mover is constant, i.e., just above the synchronous speed. However, it is a fact that the wind speed varies drastically depending on the environmental conditions and time of operation. Thus, there is a margin of speed variation. Such margin of speed variation makes wound rotor induction machines suitable for generation of wind energy. In addition to its speed variation, the wound rotor induction machine offers the additional advantage of bi-directional transfer of the rotor power which depends on the rotor speed and field speed [40]. The DFIG is essentially a wound rotor induction machine capable of operating in super-synchronous as well as subsynchronous mode. The advantages of DFIG over the fixed speed induction generators are improved power quality, reduced mechanical stress and fluctuations and excellent energy capture [19].

The operations of DFIG connected to the grid are facilitated with the rotor side and grid side converter. It is the responsibility of the inverter connected to the rotor side to provide a necessary complementary frequency to maintain the stator frequency at a constant level, despite fluctuations in the mechanical power. The control of DFIG poses a twofold problem to compensate the speed fluctuations as well as reactive power. The stability and performance of the overall setup are to be maintained in the face of model uncertainties, external noise, a variation of the internal machine parameters and speed. The problem of control becomes more involved in the case of unbalanced grid connected operations. It is well known that unbalanced operations lead to a flow of negative sequence currents which in turn may lead to localized heating as well as pulsations in the instantaneous torque. In critical applications, DFIGs must be disconnected from the grid when the voltage imbalance is more than 6% [42]. It was reported that even within this margin, torque pulsations could be reduced by injecting a compensation current in the DFIG rotor, but with their technique, the torque pulsations could not be eliminated. The design of control strategy for the DFIG requires its simplified models which can be integrated with the flexible AC transmission system (FACTs) based grid models. Such models can also be used for first-hand analysis of the overall system.

Ekanayake et al. presented a comparative study of the simplified models, wherein the authors have compared the fifth and third order model of DFIG followed by the study under faulted conditions [31]. Z. Wang and Y. Sun presented the magnitude and frequency control of grid-connected DFIG based on a synchronized model for wind power generation [43]. In this paper, the numerical differentiation based incremental model around the nominal operating point of DFIG is used. The usefulness of such models can be verified from the results presented. It is worth to mention here that the typical ratings of wind turbines are between 800kW to 3 MW, whereas wind farms range from 1 MW to 200MW [44]. A. Perdana, O. Carlson, and J. Persson presented; the dynamic response of a wind turbine with DFIG connected to the power system for the study of system response during grid disturbances [45]. Here in this paper, we provide an alternate technique to design a controller for the system considered by Ko et al. [46] using the static output feedback method. The objective of the paper is to design the controller for DFIG system by a novel SOF control technique to the performance analysis of the DFIG system. The results obtained have been compared with the existing solutions. On the other hand the serial converter is controlled by SVPWM technique. Control of DFIG based on the vector control approach with PI controllers. A DTC scheme for induction machines has been developed by the researchers to improve the performance of the vector control system. However, the primary DTC system connected with torque ripples in initial, and the low-speed operations and in switching frequency variations, which degrades the superiority of the output power Further in [47] DPC based on DTC has described. The authors included variable switching frequency due to which qualities of output power were tainted. For a constant switching frequency, DPC scheme was introduced later on in [39, 48]. But it necessary convoluted online calculations in the synchronous reference frame. A stable switching frequency DPC approach was also investigated in [49], which necessarily involved online calculations; also it is linked with fluctuation problems particularly when the generator works around its synchronous speed. However, equidistant vector based hysteresis current regulator implemented in [50]. The authors careful the discrete operation of the RSC along with analyzing the performance for stepped real and reactive power references by vector control scheme. The researchers have a complete incredibly exciting investigation of fault ride through capability. In [51], three different types of control approaches with field oriented control method has been used for control of DFIG. The most significant topic is robustness. An SMC is one of the best identified robust control techniques. In [52, 53], SMC for induction machine drive has been reported. The SMC characteristics are simplicity, disturbance rejection capability, and robust performance. On the other hand chattering, problem limits its feasibility. Best continuous SMC includes variable control, which leads to chattering. In [53] described chattering as an unwanted phenomenon of oscillations having a fixed frequency as well as amplitude. In brief Literature review is so prepared for as [54-59]. The Discrete counterpart of SMC is DSMC which has stemmed from the initiation of computers to implement control algorithms.

Hence from above literature review SOF technique is not used in DFIG so the static output feedback control method is a topical methodology to the invention of PI and PID controller for the practical systems. On the other hand the controller design for DFIG based variable speed wind turbine by using evolutionary soft computational technique has not been described. an alternate technique to design a controller for the DFIG system considered by KO et al. [46] has been described by using SOF, PSO, BFO,FFA, DE, GA optimization Technologies.

1.11.1 Control Techniques of DFIG

Control of an electric grid can be the significant part of a network operator; and this gets additional momentous while it refers DFIG based power generation [60, 61]. Wind speed variation is simultaneous with unpredictable consumers' load if the system is not under an appropriate control [62]. An enormous number of researchers have been carried out for building a robust and controllable power grid with embedded DFIGs [63-66, 67-71, 72, 73]. Whereas these explore, have behaved below the electrical scope of control, but they could divide into two essential categories such as mechanical parts and electrical devices controllers.

1.11.2 DFIG Mechanical Control Technique

The controls, as well as limitation of mechanically converted wind power at high-speed wind, are important aspects of wind energy generation. Thus, suitable controlling devices together with appropriate sensors are essential for wind turbines performance enhancement and stability under variable as well as different environmental conditions.

1.11.2.1 Pitch, stall, and active stall control

Wind turbine output mechanical power, nearby wind speed as well as density, depends on blades′ radius; pitch angle and tip speed [74, 75]. Blades pitch angle can control turbine mechanical power, as well as subsequently, its speed. However, pitch control, as well as active/reactive power regulation in wind turbine through uncertainties, is described in [76].The objective of the pitch, passive and active stall controllers are to chase this maximum power point for different wind speeds [77, 78]. In pitch control, the blades angle could be adjusted to utilize the wind energy more efficiently. The pitch angle is kept constant for low wind speeds whereas, in high gusts, the controller tries to maintain rotational speed approximately the maximum generation point of the power curve. Active-stall control merges pitch, as well as passive-stall control and also, blades, are pitched to cause stall as an alternative of feathering [79, 80].

1.11.2.2 Yaw control

Usually, yaw control is employed just for dropping yaw fault (variety of wind turbine horizontal axis from mean wind direction) in the case of wind direction changes for maximizing exerted power [81]. This control is only used by HAWG and has become a superfluous control scheme in case of perpendicularly installed wind generators [10].

1.11.2.3 Flywheel storage

On the other hand, wheel could be incorporated in mechanical controller categories, but obviously, it is not a constant control system. The main reason for a flywheel installation is its functionality as a storage mechanism since it can sustain the revolving motion of turbine much longer or more stable and smooth. Usually, wheels come with passive controllers. This research illustrates the contact of the wheel on load leveling and reactive power compensation.

1.11.3 DFIG Electrical Control Technique

Though, there are plenty of electrical control methods for DFIGs; although some of them are appropriate for wind energy conversion systems. A couple of those general control methods, which are tinted by researchers, are briefly offered in this section.

1.11.3.1 Vector control

In general, vector control uses the dynamic state relations of DFIG to establish angular speed, amplitude and instantaneous situation of current, voltage and flux linkage vectors. Vector control gives the possibility of active and reactive power control individually for generators by using the d-q synchronous frame. Prevalent researchers have been completed, which demonstrate the possibility of vector control application of DFIG for both grid-connected as well as stand-alone operations [82, 83].

1.11.3.2 Active and reactive power control

On the other hand, according to consumer demands, an active power acting a significant role in the power networks although, from an electric system behaviour point of view, reactive power has an equal distribute as active power. An induction generator requests to attract a huge quantity of reactive power for operation and control this can extensively influence the terminal voltage and a control scheme developed for the reactive power directive of wind farms made up with doubly fed induction generators and supply along with the network [84]. Even so; a technique for capacitor banks control is anticipated to facilitate grid reconfiguration in [85]. Active and reactive power controllers intended for DFIGs have been presented in [86, 87].

1.11.3.3 Direct torque control

The DTC application for induction machines proceeds towards the mid-80s. It was suggested towards overcoming the parameters′ dependency as well as the complex problem of vector control method, concerning voltage source inverters’ discrete operation. The exploration, as well as design of a DTC of a Doubly-Fed Induction Generator, applied towards a wind generation scheme as an alternative to FOC [56]. The DTC aims to control reactive power interchanged among the generator along with the grid and monitoring of power drawn from the wind turbine to track the wind turbine best process point [88]. The IMC design technique is used in the proposed method to create the controller parameters. And a constant frequency DTC algorithm is deliberate in [89]. DTC method deals with a few drawbacks for example convoluted online computation, other PI controller parameters, or failure of following machine parameter variations.

1.11.3.4 Direct power control

Direct power control for DFIG-based wind turbines has been presented in [90, 91-93]. A new DPC approach for a DFIG based wind turbine system is offered, a new extrapolative DPC techniques for the DFIM. Based on this analytical control, the scheme can operate at significantly low constant switching frequencies and allows it to carry out a power ripple minimization technique, to advance the steady-state and transient response behaviors of the machine [63]. On the other hand, numerous studies have done on DPC methods through variable switching frequency but, variable switching frequency effects in complicated besides through valuable harmonic filter along with power converter. This information contributed by researchers to static frequency converters to softer through the additional economic filter and converter design [93-96]. DPC uses in favor of DFIG within unstable network condition has also been offered in [62], in addition to power ripples have got understated inside DPC function in support of DFIG by fuzzy controller along with IDSVM in [95]. Since only a fraction of the turbine power is being used to generate stator power, which is also engaged as feedback variable into DPC controllers and also change in speed of the turbine is dependent on the difference between turbine power and total generated power. Hence, this proposal is inappropriate for generator speed control, and regarding the accuracy of speed control as well as the performance of MPPT.

1.11.3.5 Variable structure or sliding mode control

A wind turbine works just about its maximum rating in high wind speed situation to hand out maximum attainable power. During high speed or inconsistent wind, diverse oscillations manipulate tower, drive train, and generator as well as even power electronic devices work. In such circumstances, sliding mode control reduces the reference importance of the maximum power tracking controller to decrease stimulated torque vibrations. Sliding mode control constitutes into an excess of a balance between the softness of torque as well as maximum power usage (efficiency of alteration). The most exciting feature of this approach is its insensitivity to the network parameters′ variations or grid disturbances and more simplicity of operation [96]. A direct power control technique for the active and reactive power of a DFIG collectively using a nonlinear sliding mode control have been anticipated, which calculates rotor control voltage to reduce active and reactive power errors. To conquer the difficulty of conventional VSC algorithm’s insensitivity to the network parameter variation, an essential variable structure control technique in combination with a sliding mode control has been demonstrated and also a novel IVS-DTC method for a DFIG is depicted in [97].

1.11.3.6 Discrete sliding mode control

Continuous SMC described in the literature. Generally of the algorithms are carried out digitally. Perfect constant SMC admits variable switching control which contributes to chattering. Inconvenient applications of sliding mode control, engineers might have occurrence adverse experience of oscillations having a finite frequency as well as amplitude, which acknowledged as ‘chattering.' At the first phase evolution of sliding mode control theory, the chattering was the primary hindrance for its operation. Chattering is a dangerous phenomenon because it leads to little control accuracy, high wear of running mechanical parts, and high-temperature losses in power circuits. In theory ideal, sliding mode entails infinite switching frequency. While the control is constant within a sampling interval, switching frequency cannot surpass that of sampling, which extends to chattering as well. In DSMC turn independent control can guarantee to slide at all sampling instant [4, 6]. The discrete time quasi sliding-mode control systems considered; QSM as a movement of the system, such that its position forever remnants in a particular band around sliding hyperplane, is presented. The DSMC demands large control effort extending to first shoot in control. Adaptive reaching law projected in [98] limits this shoot and until results in fast convergence. A multi-rate output feedback based discrete-time sliding mode for different reaching law depicted. The anticipated algorithm used past control input for switching function as well as output samples to design controller. The chattering problem can concentrate with the proper assortment of the reaching law consideration.

1.11.3.7 Passivity control

Numerous researchers have decisive on PBC for stabilizing VSCF wind generators for energy debating. In this method, DFIG rotor voltage has usually been occupied as the control variable to control the supplying loads. A suggested passivity-based controller to govern the mechanical engine speed and accomplish stabilization via energy equilibrating, regulation of power flow in the system comprised. In [99], the operational points have been definite for the controller to exploit the generated power. The Nonlinear control schemes of VSCF wind power generator systems, particularly PBC methods, have been depicted. PBC combined with current estimator strategy reserves not only the advantages of PBC such as nonentity of uniqueness but also reduced the harmonic current tracking error stimulated by resistance as well as inductance variation. In [67, 68] wind farm control strategy is applied to sustain network intended for electromechanical oscillations damping Furthermore to stabilize the system afterward a disturbance. Therefore passivity control laws are implanted in nonlinear frame expression and their contribution to the stability of the scheme.

1.12 Emerging Issues and Control Measures of DFIG Based WECS

There are thousands of research IEEE activities (Research Publications) on DFIG control aspects during past few decades. Figure (1.23) shows the major IEEE's IP Activities on DFIG in approximation [70, 100].

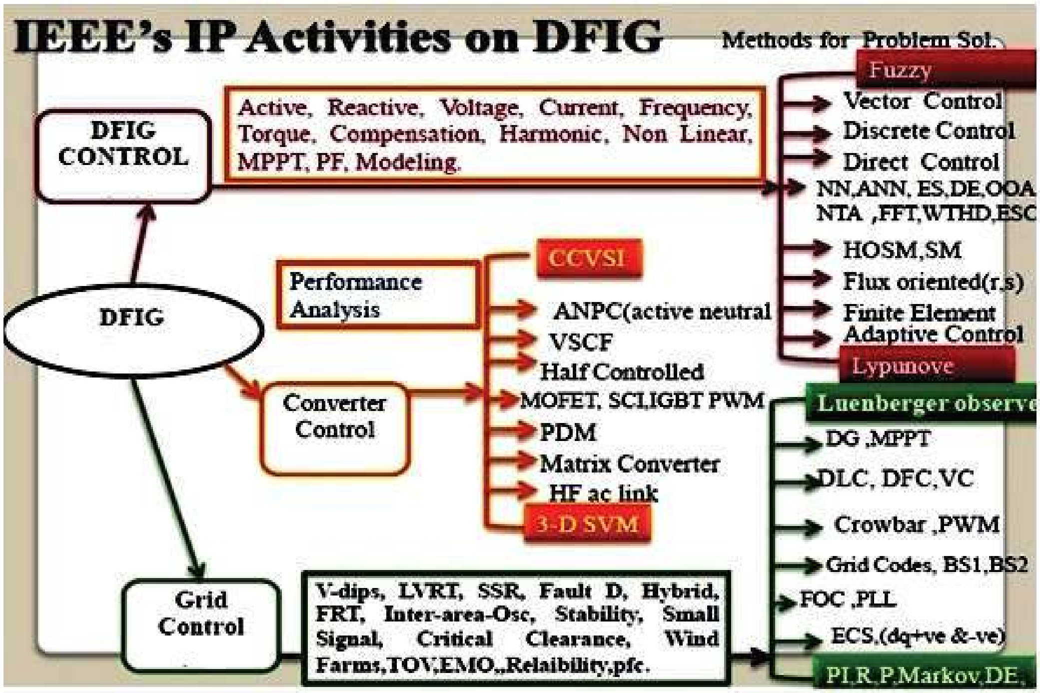


Figure 1.23: IEEE's IP Activities on DFIG

The up-and-coming Issues along with DFIG based WECS control are shown in the above Figure (1.18) and described one by one as follows.

(I) Coordinated control of frequency regulation capability

A DFIG-based WECS does not provide frequency response because of the decoupling between the output power and the grid frequency [71]. Power reserve margin also a dilemma for DFIG because of the maximum power point tracking (MPPT) function.

(II) Battery Control Operation (BESS)

The battery energy storage system (BESS) is trying to reduce power variations on the grid for uncertain wind situation, furthermore equated with existing control schemes like the maximum power point extraction at unity power factor condition of the DFIG. However, the modified rotor side of DFIG with DC link capacitor is replaced with the BESS, for tuning of controllers using the bacterial foraging optimization (BFO) technique (based on Eigenvalue) towards damp out power vibrations. Moreover, an evolutionary, iterative particle swarm optimization (PSO) scheme [94] is used for the optimal wind-battery coordination in a power system.

(III) Stator Current Harmonic Control

From introductory section of stator current, a sixth-order resonant circuit is used to remove negative sequence 5th harmonic along with positive sequence 7th harmonics currents. However, a stator current harmonic control loop is added to the first rotor current control circuit intended for harmonic suppression [101]. The effects of voltage harmonics from the grid on the DFIG are also have been discussed to the Resonant controllers, which have been widely used in harmonic control and unbalanced control for both DFIG along with power converter systems [96].

(IV) Fault Ride Through

A grid failure posed an overload condition to DFIG when it is trying to stabilize the wind farm. It would be checked the fault ride-through capability of the DFIG[92]. On the other hand, a study focused on supporting FSWT without using any FACTS device.However, a series dynamic braking resistor (SDBR) has been used to improve the FRT of large wind farms, while SDBR is connected to the rotor side converter of the DFIG to improve its Fault Ride Through capability[102].

(V) Regulation of active/reactive power

DFIG is an electromechanical device and is modeled as a nonlinear system with rotor voltages as well as blade pitch angle as inputs, along with active and reactive powers as its outputs; with uncertainties of aerodynamic and mechanical parameters [103]. For MPPT adaptive controls and fuzzy methodologies has been proposed despite not knowing the Cp-surface. However, a nonlinear controller that simultaneously enables control of the active power in both the MPT and PR(power regulation) modes with aerodynamic and mechanical parameters are known[104].

(VI) Voltage Unbalance Control

Wind energy is frequently installed in rural, isolated areas characterized by weak, unbalanced power transmission grids. The voltage unbalances factor (VUF) is defined as negative sequence magnitude divided by positive sequence quantity. The control topology is reasonably standard (based on stator-voltage-orientation) for *d-q* vector control uses. This orientation can be called grid flux oriented control. The steady-state, as well as the transient response of DFIG-based wind power production scheme under balanced and unbalanced grid voltage conditions, have been well understood[105].

(VII) Open loop rotor position: Sensorless control algorithm

The sensorless rotor position estimation schemes under open-loop category either employ a voltage integrator (for the flux estimation) or depend on inverse trigonometric computations [106]. Flux estimation based on a recursive approach, where the stator flux magnetizing current instead of the stator flux components is estimated using re-computation.

(VIII) Magnitude as well as Frequency Control

A magnitude and frequency control (MFC) approach have been anticipated for doubly fed induction generator(DFIG) in [107] along with flux magnitude and angle control (FMAC).

(IX) Control based inertia contributed by DFIG

An approach has been introduced to design a supplementary control of adjusting pitch compensation and maximum active power for the converter to improve inertial response during the transient for the DFIG[108]. On the other hand wind turbine, the frequency response is limited to a short period. The work carried out in [109] deals governor regulation, current control limits of the converter, along with auxiliary loop parameters with investigating frequency response from DFIG based wind plants.

(X) Hysteresis-Based Current Regulators

An enhanced hysteresis-based current regulator in the field-oriented vector control with PI controller for doubly fed induction generator (DFIG) based wind turbines proposed in [110]. However, its performance depends on the accurate estimation of the machine parameters, and it suffers from a complex control structure [110].

(XI) Dynamic Stability Using FACT Devices

A damping controller of the STATCOM is designed by using modern control theory to contribute Effectiveness in [111, 112]. The active operation of the nonlinear system using an optimized STATCOM controller has evaluated under a three-phase fault condition. The different control techniques such as PSS and static VAR compensator (SVC) along with STATCOM for damping undesirable inter-area oscillations in power systems have been carried out, Whereas the PI control for STATCOM is compared with various feedback control strategies, along with a linear optimal control based on LQR control [113].

1.13 Conclusion

This chapter attempts to classify and abbreviate research in wind energy extraction using DFIG, mainly controller systems, sound effects and highlighted evolution points. On the other hand, DFIGs have lots of benefits, and their competitive compensation makes them the preferred alternative for wind energy conversion systems which can associate with large power networks, but they infrequently used as stand-alone systems. Nevertheless, there are perceptible researchers, which were carried out on a small or isolated system using DFIGs but such application is rare due to control and power electronic system complication. Even though DFIG control methods and systems have been approximately for so long, this area is still fashionable among the researchers, and advanced control schemes still proposed as electrical otherwise mechanical controllers. On the other hand, these methods cover both mechanical and electrical scopes; predominantly came into electrical categories. Although installation characteristics such as site location, tower height or environmental parameters have a significant influence on DFIG electric power production, there are still a lot of networks correlated to installation aspects, which are considered by the researchers. The number of these systems coupled using DFIG impacts or mechanism along with operational concerns which studied in the last one decade is addressed in this overview. Related literature reviews have been carried out in the proposed work.

Following paper is communicated from this part of the thesis work.

- **Om Prakash Bharti**, R. K. Saket and S.K.Nagar, "A Critical Review on the Control Aspects of DFIG Based Wind Energy Conversion System," **IET Renewable Power Generation***, **under review 2018***.

1.14 Purpose and Contributions

The main purpose of this thesis is the investigation of the DFIG for aWT application both during Steady-state and transient operation. In order to analyze the DFIG during transient Operation both the control and the modeling of the system is of importance. Hence, the control and the modeling are also important parts of the thesis. The main contribution of this thesis is, to designing of controller for DFIG based WT to improve its transient performance such as "rise time", "settling time", "Peak Overshoot" etc by using optimization and soft computational evolutionary techniques such as Static output feedback (SOF) and Particle swarm optimization (PSO), Bacterial forging optimization (BFO) as well as Firefly algorithm (FFA) along with

Differential evolution algorithm (DE). And Genetic Algorithm (GA).These evolutionary techniques have several advantages over conventional methods like use of objective function no other auxiliary functions, irrespective to the type of parameters, avoid local optimization solutions, probabilistic nature and provide solution for any number of dimensions. In doing this here sixth order transfer function of DFIG model as a plant transfer function is used, with details being as follows.

1.15 Organization of Thesis

The work embodied in the thesis is organized into following seven chapters:

Chapter 1: Introduction and preview

The theme of the current research work is reported in detail. The historical development of the wind power generation technology has been presented in a chronological manner. Further, chapter also explains the fundamental concepts of the DFIG based wind turbine for WECS with its possible present and future applications along with its major salient features. Moreover, some available studies related to DFIG based WT are reviewed along with literature survey. On the other hand a critical review of the DFIG based WT along with control aspects for wind energy conversion system with emerging issues form last one decade has been described. The study starts with describing widespread perception on wind energy and commonly used a generator in wind conversion. Then it presents additional particulars on DFIGs active modes and utilization. It is followed by DFIG control methods in addition to overviews of different engaged electrical and mechanical controlling methods. Based on the review DFIG has compensation regarding electrical, mechanical as well as economic views. DFIG has the main promising prospect for WECS in power generation to harmonize the conventional systems.

Finally, this chapter concludes with the motivation, research objectives, and organization of thesis.

Chapter 2: The modeling and controller design for the DFIG by using SOF technique

The modeling and controller design for the DFIG driven by variable speed wind turbine by using SOF technique is described. The mathematical model of the DFIG, its converters, and their controllers have discussed appropriately. The controller design for DFIG based wind energy generation system using SOF technique with LMI approach is described. The obtained results are compared with the supervisory controller techniques for performance improvement of the DFIG-based wind turbine to wind energy conversion system.

Chapter 3: The controller design for DFIG using particle swarm optimization technique

The controller design for doubly fed induction generator (DFIG) driven by a variable speed wind turbine using particle swarm optimization technique is described. The controller design for DFIG based WECS using PSO technique and its fitness functions are described in detail. The responses of the DFIG system regarding terminal voltage, current, active-reactive power and DC-Link voltage along with generator speed have slightly improved with PSO based controller. Finally, the obtained output is equated with a standard technique for performance improvement of the DFIG based wind energy conversion system.

Chapter 4: Ccontroller design for DFIG by using Bio-inspired technique

The bio-inspired technique is used to controller design for doubly fed induction generator-based variable speed wind turbine. That is based on exploiting the two efficient swarm intelligence based evolutionary soft computational method, i.e., Particle Swarm Optimization (PSO) and Bacterial Foraging Optimization (BFO) to design the controller for low damping plant of the DFIG. Wind energy overview and DFIG based WT component with operating principle as well as the equivalent circuit model of the DFIG, have been discussed appropriately. The controller design for DFIG based WECS using PSO and BFO technique along with its fitness functions are described in detail. The responses of the DFIG system regarding terminal voltage, current, active-reactive power and DC-Link voltage along with generator speed have slightly improved with PSO based controller in comparison with BFO based controller. Finally, the obtained output is equated with a standard technique for performance enhancement of the DFIG based wind energy conversion system.

Chapter 5: Controller design for the DFIG by using Firefly algorithm techniques

The Controller design for doubly fed induction generator-based variable speed wind turbine by using evolutionary soft computational techniques that is based on exploiting the three efficient swarm intelligence based method, i.e., Firefly algorithm (FFA) ,Differential Evolution Optimization (DEO) and Genetic Algorithm. The controller design for DFIG based WECS using FFA, DEO and GAO technique along with its fitness functions are described in detail. The responses of the DFIG system concerning terminal voltage, current, active-reactive power and DC-Link voltage along with generator speed have slightly improved with FFA based controller in comparison with DEO& GAO based controller. At last, the obtained output is equated with a usual technique for performance enhancement of the DFIG based wind energy conversion system.

In this chapter, the proposes to design of PID controller for DFIG base WT to improve its transient performance such as “rise time”, “settling time”, “Peak Overshoot” etc by using three evolutionary techniques such as Firefly algorithm (FFA), Differential evolution algorithm (DE) and Genetic Algorithm (GAO). These evolutionary techniques have several advantages over conventional methods like use of objective function no other auxiliary functions, irrespective to the type of parameters, avoid local optimization solutions, probabilistic nature and provide solution for any number of dimensions. In doing this here sixth order transfer function of DFIG model as a plant transfer function is used. In this manuscript the results of three evolutionary algorithms compared and concluded that FFA-based controller better option for DFIG-based wind turbine scheme to the wind energy conversion systems.

Chapter 6: On-off control based MPPT & Reliability assessment of DFIG based WT

An on-off Control method is used for MPPT and anticipated to control the rotor side converter of DFIG based wind turbine connected to the grid, which is trying to keep the torque within the optimal value at which the maximum power is obtained. The Grid Side Converter is controlled in such a way to assure a smooth DC voltage as well as ensure sinusoidal current on the network. Finally the Reliability of DFIG based WT with performance analysis are described, which builds on the reliability of its components by using Markov process.

Chapter 7: Summary and conclusion

Finally, in this chapter, the research work embodied in the present thesis has been summarized, and the significant conclusions have been drawn from the major findings. Furthermore, this chapter also includes the future prospective of current research work.

In chapter 2, the controller design by using SOF technique for DFIG has been described in details. On the other hand, a critical review of the DFIG based WT along with control aspects for wind energy conversion system with emerging issues are demonstrated in the present chapter.