# Chapter 1

# Introduction

With the projection of the world population there is an increasing demand for energy which would result in frequent depletion of fossil fuels causing a great increases of the energy price in the future. However renewable energy is considered to be an alternative for the fossil fuels that is why most of modern countries are focusing their researches on renewable energy [1].

## 1.1 Wind Energy

Wind energy is one of the most important and promising sources of renewable energy all over the world, mainly because it is considered to be nonpolluting and economically viable. At the same time, there has been a rapid development of related wind turbine technology [2–3].
Wind energy is basically changing kinetic energy of the wind into rotational energy. The electrical generator then converts this rotational energy into electrical energy.
The advantages of using the wind energy are as follows:

1- Wind energy is friendly to the surrounding environment.
2- Wind turbines take up less space than the average power station.
3- Newer technologies are making the extraction of wind energy much more efficient.
4- Wind turbines are a great resource to generate energy in remote locations.
5- When combined with solar electricity, this energy source is great for developed and developing countries to provide a steady, reliable supply of electricity.

However, there are some disadvantages such as:

1- The strength of the wind is unreliable.
2- Wind turbines generally produce less electricity than the average fossil fuelled power station.
3- Wind turbine construction can be very expensive and costly to surrounding wildlife during the build process.
4- High noise pollution.
5- Protests and/or petitions usually confront any proposed wind farm development.

## 1.2 Wind Turbine

Wind turbines can be divided into two main types, horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT) based on which direction they spin either horizontally or vertically. Figure 1.1 shows these two types.

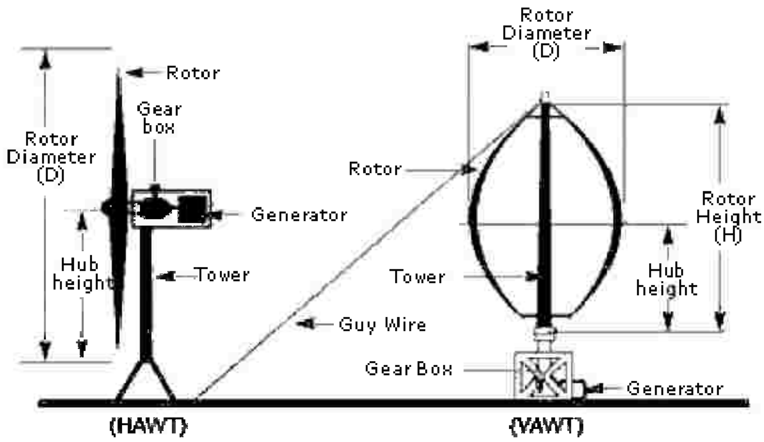


Figure 1.1 Types of Wind turbines

### 1.2.1 Horizontal Axis Wind Turbines

Let's first discuss Horizontal Axis Wind Turbines (HAWT). HAWT has a similar design to the wind mill; it has blades that look like a propeller that spin on the horizontal axis. They have the main rotor shaft and electrical generator at the top of a tower, and they must be pointed into the wind. The turbines are pointed to the wind using simple wind vane placed square with the rotor for small turbines or using a wind sensor coupled with a servo motor for large ones. In case of large turbines a gear box is used this turns the slow rotation of the rotor into a faster rotation that suitable for driving an electrical generator. Horizontal Axis Wind Turbines are either upwind or downwind turbines [4-5].

#### 1.2.1.1 Upwind turbine

The rotor that on an upwind turbine is in front of the unit, positioned similar to a propeller driven airplane .To keep it oriented into the wind, a yaw mechanism such as a tail is needed. The advantages are the reduced tower shading. The air would start to bend around the tower before it passes it so there is some loss of power from the interference, just not the degree as in the downwind turbine.

The disadvantages are the extended nacelle that is required to position the rotor far enough away from the tower to avoid any problems with a blade strike. The blades themselves must be somewhat stiff to avoid bending back into the tower. This would mean that the point where the blade attaches to the rotor hub will be stressed during high, gusty wind conditions.

#### 1.2.1.2 Downwind turbine

The downwind turbine has its rotor on the back side of the turbine. The nacelle typically is designed to seek the wind, thus negating the need for a separate yaw mechanics.

The Advantage is that the rotor blades can be flexible since there is no danger of the tower strike. The flexing blade has two advantages. They are relatively cheap .They can relieve stress on the tower during high or gusty wind conditions since the flexing allows some wind load to be transferred directly to the blades instead of the tower. The Proven has a hinged design that allows the blade to flex back to dissipate energy for speed control.

The Disadvantage the flexible blade advantage can also be a disadvantage as the flexing may fatigue the blades .Tower shadow is problem with a downwind machine since the rotor blade actually passed behind the tower. This can cause turbulence and increased fatigue on the unit [4]. The advantages of HAWT are as follows:

1. The tall tower base allows access to stronger wind in sites with wind shear.
2. High efficiency.

The disadvantages of HAWT are as follows:

1. Massive tower construction is required to support the heavy blades, gearbox, and generator.
2. Components of a horizontal axis wind turbine (gearbox, rotor shaft and brake assembly) being lifted into position.
3. Their height makes them obtrusively visible across large areas, disrupting the appearance of the landscape and sometimes creating local opposition.
4. Downwind variants suffer from fatigue and structural failure caused by turbulence when a blade passes through the tower's wind shadow.
5. HAWTs require an additional yaw control mechanism to turn the blades toward the wind.
6. HAWTs generally require a braking or yawing device in high winds to stop the turbine from spinning and destroying or damaging itself [6].

### 1.2.2 Vertical Axis Wind Turbines

On the other hand Vertical axis wind turbines, as shortened to VAWTs, have the main rotor shaft arranged vertically. With a vertical axis, the generator and other primary components can be placed near the ground, so the tower does not need to support it, also makes maintenance easier [4]. The advantages of VAWT are as follows:

1. No yaw mechanism is needed.
2. A VAWT could be located nearer the ground, making it easier to maintain the moving parts.
3. VAWTs have lower wind startup speeds than the typical the HAWTs.
4. VAWTs may be built at locations where taller structures are prohibited.
5. VAWTs situated close to the ground can take advantage of locations where rooftops, mesas, hilltops, ridgelines, and passes funnel the wind and increase wind velocity.

Disadvantages of VAWT are:

1. Most VAWTs have an average low efficiency than HAWTs.
2. Having rotors located close to the ground where wind speeds are lower due and do not take advantage of higher wind speeds above [6].

Tables 1.1 indicate comparisons between VAWTs and HAWTs.

Table 1.1 Comparisons between VAWTs and HAWTs

| Points | HAWTs | VAWTs |
|---|---|---|
| Source of producing electricity | Wind | Wind |
| Size of industrial machine | Large | Large |
| Use of electrical generator | Yes | Yes |
| Fanatical feasibility | High | Low |
| Operating speed | From 3m/sec to 50m/sec | From 1m/sec to 20m/sec |
| Range of power production | From 1kw to 6 Megawatts | Less than 50 kw |
| Maintenance | Relatively hard | Easy |
| Size | Commercial | Non-commercial (small applications) |
| Positioning | Must face the wind | don't need to face wind |

## 1.3 Generators

Basically, any wind turbine could be equipped with any type of three-phase generator. Currently the demand of the electrical grid can be achieved by using frequency converters either the generator is supplies alternating current (AC) of variable frequency or direct current (DC). Table 1.2 shows the different types of generators used in wind turbines [7-8].

Table 1.2 Different types of generators used in wind turbines

| Synchronous generator | Asynchronous (induction) generator |
|---|---|
| 1- Wound rotor generator (WRSG) | 1-Squirrel cage induction generator (SCIG) |
| 2- Permanent magnet generator (PMSG) | 2- Wound rotor induction generator (WRIG)<br>A-Opti-Slip induction generator (OSIG)<br>B- Doubly-fed induction generator (DFIG) |

### 1.3.1 Synchronous generator

Synchronous machine is the most suitable machine for full power control when connected to the grid through a power electronic converter. The two main goals of the converter are:

1. To act as an energy buffer for the power fluctuation caused by inherently gusting wind energy and for transient coming from the net side.
2. To control the magnetization and to avoid problems by remaining synchronized with the grid frequency.

**Advantages are:**

1. Does not need a reactive magnetizing current
2. If a suitable number of poles is used the synchronous generator can be driven without the use of gear box.

**Disadvantages are:**

1. Expensive.
2. Mechanically more complicated.

### 1.3.1.1 Wound rotor synchronous generator (WRSG)

The (WRSG) shown in Figure 1.2 does not need any further reactive power compensation system. The rotor winding is excited using a direct current by using slip rings and brushes or with a brushless exciter with a rotating rectifier. The speed of the synchronous generator is determined by the frequency and by the number of poles of the rotor [7-9].

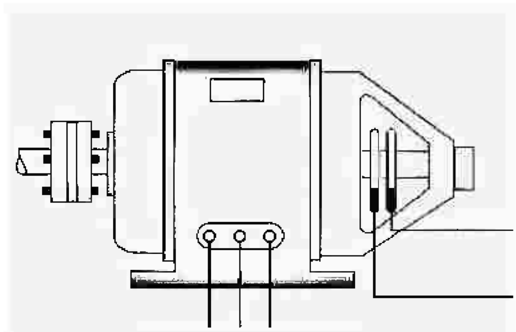

Figure 1.2 Wound rotor synchronous generator

**Advantages are:**

1. Does not need any further reactive power compensation.
2. Doesn't need a gear box.

**Disadvantages are:**

1. Rotation speed is restricted by supply grid frequency.
2. Large and heavy generator and a full-scale power converter have to be installed.

### 1.3.1.2 Permanent magnet synchronous generator (PMSG)

The stator of the permanent magnet generator (PMSG) is wound and the rotor is provided with permanent magnet pole system and may have salient poles or cylindrical as shown in Figure 1.3. Salient poles are commonly used in slow speed machines and it may be the most useful version for an application such as wind generator. Typically low speed synchronous machine are salient pole type [10].

**Advantages are:**

1. Self excited.
2. Can operate at high power factor.
3. High efficiency compared to induction machine.
4. Power generation can be done at any speed.
5. Does not need a gear box.

**Disadvantages are:**

1. Expensive.
2. Requires the use of full scale power converter to adjust voltage and frequency of generation.
3. Problems during startup, synchronization and voltage regulation.
4. Magnetic materials are sensitive to temperature.

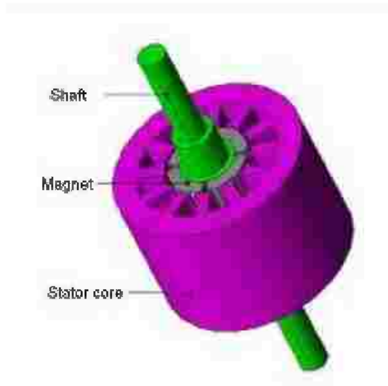


Figure 1.3 Permanent magnet synchronous generator

### 1.3.2 Asynchronous (induction) generator

The most commonly used in wind turbines is the induction generator. Induction generators are separately excited which means it must receive its excitation from another source and consumed reactive power this power is either supplied form grid or by power electronics system. If the machine's speed is some value greater than the synchronous speed for the power system to which it is connected, the direction of its induced torque will reverse and it will act as a generator. The greater the torque applied to its shaft (up to certain limit), the greater its resulting output power [7].

**Advantages are:**

1. Robust and mechanical simple.
2. Cheap.

**Disadvantages are:**

1. Separately excited, need separate exciting source.
2. Gearbox is required.

#### 1.3.2.1 Squirrel cage induction generator (SCIG)

The speed of the SCIG shown in Figure 1.4 changes by only a few percentages because of the generator slip caused by changes in wind speed. Therefore, this generator is used for constant-speed wind turbines both the generator and the wind turbine rotor are coupled through a gearbox as the optimal rotor and generator speed ranges are different. Wind turbines based on a SCIG are typically equipped with a soft-starter mechanism and an installation of reactive power compensation. SCIG have a steep torque characteristics and therefore fluctuation in wind power are transmitted directly to the grid which are critical during grid connection of the wind turbine where the in-rush current could be up to 7–8 times the rated current.

In a weak grid, this high in-rush current can cause severe voltage disturbances. Therefore, the connection of the SCIG to the grid should be made gradually in order to limit the in-rush current [7-9].

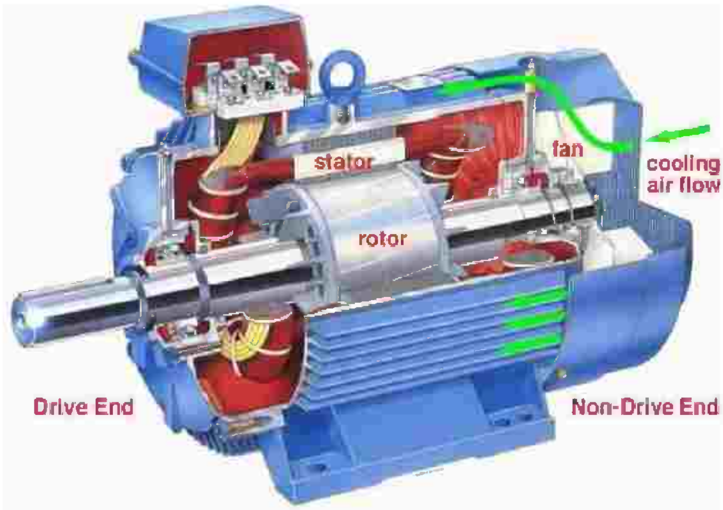


Figure 1.4 Squirrel cage induction generators

**Advantages are:**

1. Mechanically simple.
2. High efficiency.
3. Low maintenance requirements.

**Disadvantages are:**

1. Need gearbox.
2. Consume reactive power (separately excited).
3. Low full load power factor.
4. High transmission loss.
5. Electrical transients occur during switching.

### 1.3.2.2 Wound rotor induction generator (WRIG)

The wound rotor induction machine shown in Figure 1.5 is basically used as a motor, but due the characteristic of the machine typically used as a generator in the applications that require varying speed of the machine's shaft .the electrical characteristics of the rotor can be controlled from the rotor terminal, and thereby a rotor voltage can be injected. There are two types of the wound rotor induction generator (WRIG) the Opti-Slip induction generator and the doubly feed induction generator [7].

**Advantages are:**

1. Power can be extracted or impressed from the rotor circuit.

**Disadvantages are:**

1. Expensive.
2. Not robust.
3. Need a gearbox.
4. Need reactive power supply.

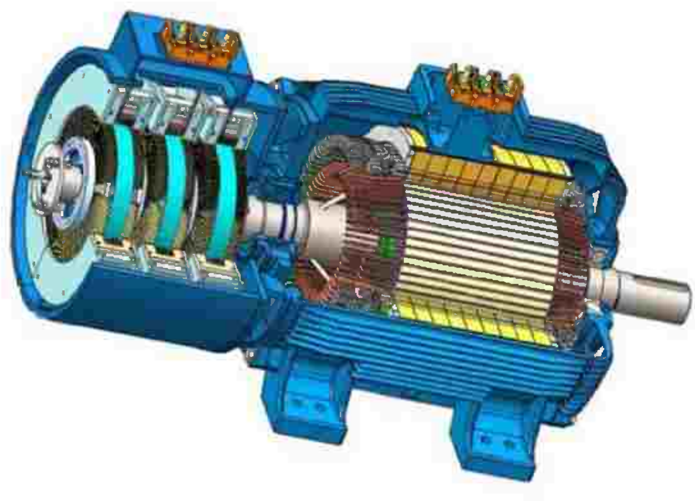

Figure 1.5 Wound rotor induction machine

**A. Opti-Slip induction generator (OSIG)**

An interesting variation of the variable slip induction generator avoids the problem of introducing slip rings, brushes, external resistors, and maintenance altogether.
By mounting the external resistors on the rotor itself, and mounting the electronic control system on the rotor as well, you still have the problem of how to communicate the amount of slip you need to the rotor. This communication can be done very elegantly, however, using optical fibre communications, and sending the signal across to the rotor electronics each time it passes a stationary optical fibre.
The Opti-Slip feature was introduced by the Danish manufacturer Vestas [7] in order to minimize the load on the wind turbine during gusts. The Opti-Slip feature allows the generator to have a variable slip and to choose the optimum slip resulting in smaller fluctuations in the drive train torque and in the power output. Basically it's a (WRIG) with variable resistance connected to the rotor terminal.

**Advantages are:**

1. Simple circuit topology.
2. No need for slip rings.
3. Reduction in mechanical loads and power fluctuations caused by gusts.

**Disadvantages are:**

1. Need reactive power supply.
2. The speed range is typically limited.
3. Only poor control of active and reactive power is achieved.
4. Reduced efficiency, because the slip power is dissipated in the variable resistance as losses.

**B. Doubly-fed induction generator (DFIG)**

The DFIG consists of a WRIG with the stator windings directly connected to the constant-frequency three-phase grid and with the rotor windings mounted to a bidirectional back-to-back IGBT voltage source converter The term ‘doubly fed’ refers to the fact that the voltage on the stator is applied from the grid and the voltage on the rotor is induced by the power converter. This system allows a variable-speed operation over a large, but restricted, range. The converter compensates the difference between the mechanical and electrical frequency by injecting a rotor current with a variable frequency. Both during normal operation and faults the behavior of the generator is thus governed by power converter and its controllers. The power converter consists of two converters, the rotor-side converter and grid-side converter, which are controlled independently of each other. The main idea is that the rotor-side converter controls the active and reactive power by controlling the rotor current components, while the grid side converter controls the DC-link voltage and ensures a converter operation at unity power factor (i.e. zero reactive power) depending on the operating condition of the drive, power is fed into or out of the rotor in an over synchronous situation, it flows from the rotor via the converter to the grid, whereas it flows in the opposite direction in a sub synchronous situation. In both cases sub synchronous and over synchronous the stator feeds energy into the grid [8].

**Advantages are:**

1. Able to control reactive power.
2. Decouple active and reactive power control by independently controlling the rotor excitation current.
3. Can be magnetized from the rotor circuit.
4. Capable of generating reactive power.
5. Wide speed range.
6. Increased efficiency.

**Disadvantages are:**

1. Inevitable need for slip rings.
2. Still need reactive power supply.
3. Wide speed range means expensive converter.

### 1.3.3 Different types of generators connected with the wind turbine

Synchronous or asynchronous generators are connected to the wind turbine through gear box in case of asynchronous generators, or without gear box in case of synchronous generators. There are four different types of connection depending on the type of the generator. Type A used only in fixed wind speed. Type B, type C, and type D mostly used because it works at variable speed [ 8-9 ]. Figure 1.6 show the different types of generators connected with the wind turbine.

Table 1.3 shows comparisons between synchronous and asynchronous generators. From these comparisons it is clear that the DFIG is preferable because of its ability to generate at wide range of speed, cheaper, can be self-excited, simple, robust, and high efficiency but it requires a gear box.

Currently, mainly, three wind turbine concepts dominate the market: 1) fixed-speed wind turbines with an induction generator directly connected to the grid, 2) gearless wind turbines with a power electronic converter connected between the stator and the grid, and 3) systems with DFIG, i.e., a slip-ringed wound-rotor induction generator, where a power electronic converter is connected between the rotor circuit and the grid. The latter is currently the most popular one [10], due to its high energy efficiency and due to the fact that a power electronic converter with a rating of only 20%–30% of the rated wind turbine power is needed. However, it is the most difficult one to control and also to model.

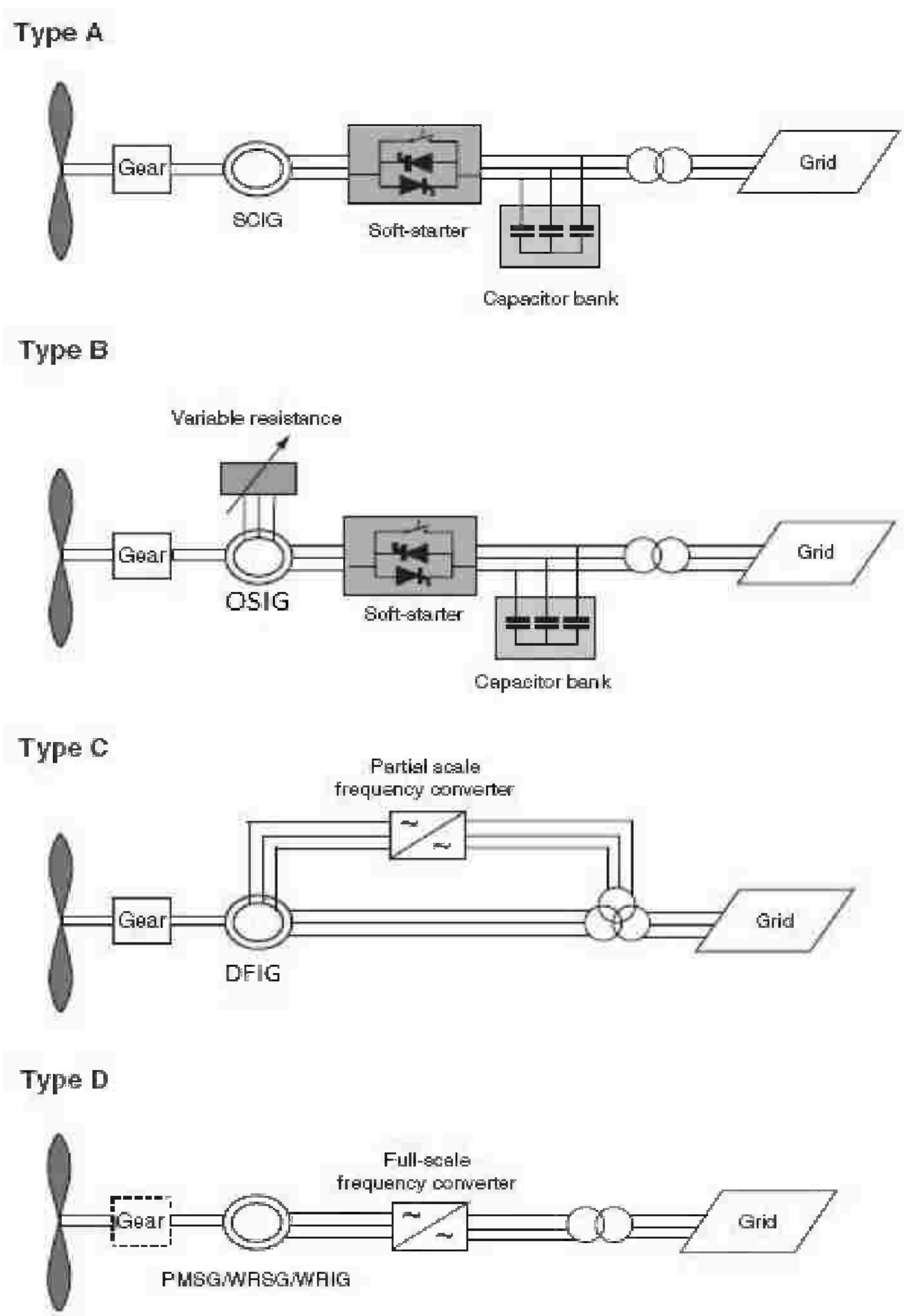


Figure 1.6 Different types of generators connection

Table 1.3 Comparisons between synchronous and asynchronous generators

| Points | Induction | | | | Synchronous | |
|---|---|---|---|---|---|---|
| | SCIG | WRIG | OSIG | DFIG | WRSG | PMSG |
| Excitation | Not self excited | Not self excited | Not self excited | Can be self excited | Self excited | Self excited |
| Price | Cheap | Expensive related to SCIG | Cheap | Cheap | Expensive | Expensive |
| Mechanical design | Simple and robust | Simple but not robust | Simple and robust | Simple and robust | Complicated | Complicated |
| Use of gear box | Must use gearbox | Must use gearbox | Must use gearbox | Must use gearbox | Gear box is not essential | Gear box is not essential |
| Speed range operation | Restricted | Restricted | Wide but restricted 0-10% | Wide | Restricted | Restricted |
| Efficiency | Moderate | High | Moderate | High | Moderate | High |

## 1.4 Thesis Objective

The main objective of this thesis is to model, simulate and control a variable speed wind turbine driven DFIG for both stand-alone operation and grid connected operation.

## 1.5 Scope of the Thesis

This thesis consists of six chapters organized as follows:

- Chapter1: Introduction, in this chapter a brief introduction to the wind energy system components (wind turbine and generators) was presented. A comparisons between synchronous and asynchronous generators was done.
- Chapter 2: D-Q model of induction machine, this chapter presents a dynamic (d-q) model of induction machines. Simulation of induction motor was carried out using Simulink software and results were compared with experimental results.
- Chapter 3: Stand-alone doubly-fed induction generator, in this chapter both stand-alone uncontrolled and controlled DFIG were discussed and simulated using Simulink software and the results were verified experimentally.
- Chapter 4: Space-Vector Controlled Doubly-Fed Induction Generator, this chapter presents a stand-alone doubly-fed induction generator controlled using space-vector control technique to improve the stator voltage waveform.
- Chapter 5: Grid-Connected Doubly-Fed Induction Generator, in this chapter a study of a DFIG connected to a utility grid was presented. The study includes variable speed operation of the DFIG both below and above synchronous speed.
- Chapter 6: Conclusion and future work, this chapter summarizes the conclusions and the future work.