CHAPTER 1

INTRODUCTION

1.1 RESEARCH BACKGROUND

In recent years, the world has experienced a steady increase in energy demand (International Energy Agency 2010a). This demand is due to several factors such as population growth and the increased power consumption of the industrial, commercial and residential sectors (Eric Martinot et al. 2002). In general, it can be said that the power consumption is directly related to economic development and social development of a country, as a nation the more developed, the higher your energy consumption per capita (International Energy Agency 2005). However, emerging countries such as China and India, have shown a great average annual growth in energy demand (International Energy Agency 2015), where growth is mainly taken in the manufacturing sector, followed by the household sector.

The imbalance between the energy supply and demand is a widespread phenomenon that requires serious efforts for the Government of India to increase the energy supply. India imports about 80% of its oil. There is a risk of increase in oil import, creating serious problems for energy security in the future of India (Reports 2016). There is also a significant risk of low thermal power plant capacity due to lack of indigenous coal in the coming years due to production and logistical constraints, and increasing dependence on imported coal. In recent years, a large accumulation of gas reserves and production of biogas are likely to ease its energy requirements
only to a limited extent. The difficulties are also being faced by large hydro and nuclear power. Because of the shortage in the supply of electricity, large amounts of diesel and oil are used by all sectors such as industrial, commercial, institutional and residential. The shortage of electricity in rural areas leads to use on a wide range of kerosene. It must be reduced, because they lead to high costs in the form of subsidies and increasing dependence on imports from other countries.

The energy supply is largely based on energy sources derived from fossil fuels (coal, oil, etc.) as shown in Figure 1.1 (a). This profile of energy supply has motivated numerous discussions on the direction to be taken, since the nature reserves of these fuels are not persistent, which will lead to the reduction of its reserves in a period of time that can span some decades or, in hopeful viewpoint, a few hundred years (Bose 2010) as shown in Figure 1.1 (b). Because of this perspective, and the environmental effects that have been revealed in recent years, several studies have been conducted to use the technical and economic feasibility of introducing alternative energy sources (Bose 2010).

![Figure 1.1](source: Bose 2010)

**Figure 1.1** (a) Global energy scenario, (b) Idealized energy-depletion curves of the world

(Source: Bose 2010)
This is mainly due to price changes of these fuels and the need to reduce emissions of gases that cause the greenhouse effect. Moreover, in countries such as China and India, the most commonly used primary source is the coal, turning China and India into the largest emitters of CO$_2$ and other gases causing the greenhouse effect (International Energy Agency 2010b). Renewable energy can play an important and strategic role in the diversification and expansion of energy, and also reduce emissions of CO$_2$.

Many developed countries have diversified its energy matrix by investing primarily in renewable sources and reducing consumption of fossil fuels. Renewable energy can make a significant contribution in each of the areas mentioned above. In this context, the role of renewable energy must be seen. Alternative energy such as photovoltaic, wind energy, bio-fuel and fuel cell become the solution to the country's energy needs. The renewable energy is an important element in the energy planning process in India for more than two decades. As at end of February 2016, the total installed capacity of Renewable Energy Sources (RES) in India was amounted to 81,525 MW, which is about 28.24% of the total capacity of 288,665 MW installed and it is given in Table 1.1 (Indian Electricity Scenario 2016). The renewable energy sources include power generation from Small Hydro Project, Biomass Gasifier, Biomass Power, Urban & Industrial Waste Power and Wind Energy.

**Table 1.1 Total installed capacity in India**

<table>
<thead>
<tr>
<th>Fuel (as on 29.02.2016)</th>
<th>MW</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total Thermal</strong></td>
<td>201,360</td>
<td>69.76</td>
</tr>
<tr>
<td>Coal</td>
<td>175,858</td>
<td>60.92</td>
</tr>
<tr>
<td>Gas</td>
<td>24,509</td>
<td>8.49</td>
</tr>
<tr>
<td>Oil</td>
<td>994</td>
<td>0.34</td>
</tr>
<tr>
<td><strong>Hydro (Renewable)</strong></td>
<td>42,703</td>
<td>14.79</td>
</tr>
<tr>
<td><strong>Nuclear</strong></td>
<td>5,780</td>
<td>2.00</td>
</tr>
<tr>
<td><strong>Renewable Energy Sources (MNRE)</strong></td>
<td>38,822</td>
<td>13.45</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>288,665</td>
<td>100.00</td>
</tr>
</tbody>
</table>
1.2 DISTRIBUTED GENERATION

Due to its features, renewable sources have normally been directly employed in distribution networks at lower power to 30 MW through photovoltaic generation, biomass, small hydro and wind, meeting the principle of Distributed Generation (Chowdhury et al. 2009). The distributed generation allows the integration of different types of renewable systems and non-renewable systems, reducing the cost of investment in transmission and distribution system. Sources of Distributed Generation (DG) may be renewable such as Wind, Photovoltaic cell, Fuel cell, etc., or from non-renewable such as Internal Combustion Engines, Combined Cycle Engines, Combustion Turbines and others (Chowdhury et al. 2009).

Distributed generator units within an electrical distribution system offer technical advantages in terms of power quality, reliability, efficiency and system supervision. In the system shown in Figure 1.2, when the grid supply is not available, distributed sources and energy storage devices must supply the demand of the local loads, keeping the voltage and frequency with acceptable values to maintain power quality. When utility power is restored, the interconnection switch can only be closed when the synchronizing between MicroGrid and the network is assured, which requires constant monitoring of voltage on both sides of the connection. As the existing distributed generating source can produce variable DC or AC power, it becomes necessary to use an interface device to obtain an AC power with a fixed frequency. This interface can be a synchronous or an asynchronous static power converter. For renewable sources such as variable speed wind generators, micro turbines and photovoltaic cells, a power electronic converter is used as an interface device, that has main functions to control the active power delivered to the utility grid and also to extract the maximum power from the primary source.
Figure 1.2  Diagram of a typical MicroGrid including local loads, the Distributed Generators (DG) and the energy storage device (SD)  
(Source: Chowdhury et al. 2009)

The DG concept involves measurement, control and command that articulate the operation of the generators and the eventual control of loads (power ON / OFF) to adapt to the energy supply. The power generation near the consumer has become the rule in the first half of the century, when the industrial energy was practically all generated locally. From the 40s, the generation in large power plants has become cheaper, reducing the interest of
the consumer in DG and, as a consequence, technological development to encourage this type of generation also stopped. With the end of the monopoly of electricity generation in the mid-80s, the development of technologies was again encouraged with visible results in cost reduction.

The advantages of DG pertaining to the society, the environment and the electricity sector are as follows (Robert Lasseter et al. 2002; El-Khattam & Salama 2004).

- Superior quality and reliability of supply through DG technologies because the electrical system does not accept frequency variations and/or voltage;
- Increase the reliability of supply to consumers;
- Electricity generated by DG has a lower cost;
- An increase in the generation mix leads to increased safety of energy supply;
- Creation of jobs and stability in production by the domestic/industry producing economic development;
- Due to the use of own resources of the region, there is a contribution to local development (social and economic);
- Reducing Green-House Gas (GHG) emissions due to the use of distributed energy resources;
- Minimizing environmental impacts by reducing the big needs of generation facilities and extensive transmission lines;
- Reducing the use of non-renewable energy sources;
- Reducing deforestation;
- Possibility of improving energy efficiency;
- Appropriate use of renewable resources;
- DG is economically attractive since it reduces the costs and investments in substations, reduce losses in transmission lines and reactive power and increases voltage stability;
- The diversity of private investment generated by DG tends to expand the number of generating agents and participants, which can represent a great opportunity in commercial sector;
- For increase in demand, deployment time of DG is lesser than the additions to the centralized generation and reinforcement of their transmission and distribution;
- Decrease in dependence of generating units dispatched centrally, keeping close to the load centers;
- Contribution to the reduction of risk associated with planning errors and price fluctuations in the electric system.

### 1.3 MICROGRID

In fact, the low voltage micro sources with a power rating of few kW are connected together to increase the power quality and reliability of power supply to end consumers and an increase in the penetration of renewable energy resources to the distribution systems. It also brings benefits by lowering the investment for the future expansion of the power system network. A MicroGrid (MG) is generally seen as a single flexible and controlled unit to regulate energy and maintain the power quality with security and reliability. In this perspective, MG can be defined as a low voltage network (for example, a small urban area, an industrial complex, an educational institution) and several small generation systems connected to it.
providing power to the local loads. With the Power Electronics Interface (PEI), an MG can be the bridge between the micro-sources, Energy Storage Devices (ESD), local loads and the supply grid. The MG can operate in DC and/or AC. The Consortium for Electric Reliability Technology Solutions originated the research on the impact of connecting a large number of distributed energy resources for low voltage networks in order to increase the reliability of electric power system and they developed the MG (Hatzigioryiou & Sakis Meliopoulos 2002) concept.

MG is viewed as a controlled part within the power system from the grid side interface and can be operated by the central controller. On the contrary, MG is considered as a small-scale power system from the customer side to optimally supply the high reliability and effective power to the customers according to their demand. The structure of a typical MG is as shown in Figure 1.3. It consists of micro-sources, energy storage devices, loads, circuit breakers (CB), local controllers (LC) and main controller (MC).

![Figure 1.3 Structure of a typical MicroGrid](image-url)
MG is intended to operate in two different situations (Xinhe Chen et al. 2010). Interconnected Mode: MG is connected to a local main grid, and it is supplying certain amount of power to the low voltage grid or consuming power from the low voltage grid. Islanded Mode: MG works autonomously in a way similar to physical islands, when MG has disconnected from the low voltage network. The disconnection may be due to disturbance or any other problem occurred in the grid.

The main controller and the local controllers should maintain the power quality, monitor the utility grid and local grid and must communicate with other controllers to provide reliable service. Since the MG is intended to operate in two modes, the controller has to be designed accordingly when to isolate the MG from the utility grid and to detect the fault in both modes. Thus, high-speed fault detection devices are mandatory in the MG (Vilathgamuwa et al. 2006).

DC MicroGrid system has the following advantages over the AC MicroGrid (Abu-Sharkh et al. 2006; Lee et al. 2010; Estefanía Planas et al. 2015):

- synchronization is not required
- the voltage sag, voltage unbalance and harmonics in voltage are not presented in DC MicroGrid
- the various sources are controlled in a coordination manner to improve the power quality and system efficiency
- energy storage devices are used to compensate the voltage and power fluctuations in MicroGrid
• In addition to reducing emission of CO$_2$ and financial costs, MicroGrids can provide the best solution to increase the penetration of renewable energy sources in a distribution system.

The disadvantage of this configuration is that the entire system does not provide AC power when the inverter fails. In addition, the multiple power electronic converters are required in a DC MicroGrid and it increases the power loss in the system.

1.3.1 General Topology of Distributed Energy Systems

A comprehensive block diagram of a power electronics interface with distributed energy sources is shown in Figure 1.4. The PEI converts the power obtained from distributed energy sources to power at rated voltage for DC grid and rated voltage and frequency for AC grid. The power flow may be unidirectional or bidirectional and it depends upon the type of source. If the source is an energy storage device, then the power flows in both directions between the source and the grid.

![Figure 1.4 Distributed energy resources with power electronics interface](image.png)
Depending on the input source, the first stage converter may be AC-DC or DC-DC converter, which is used to convert the variable AC voltage with variable frequency to constant DC or variable DC voltage to fixed DC voltage. Then the fixed DC voltage may be directly fed to the grid or local load through PCC, if it is DC grid and/or DC load. Otherwise, the fixed DC voltage is again inverted to AC voltage by using DC-AC converter and it is filtered to obtain an effective power. Then it is supplied to the AC grid and/or AC local loads. The observer and controller consists of sensing and protection units, and it will monitor the system. If there is any fault occurred in the system, then the controller will isolate the system from the grid. The controller also provides human-machine interface, communications interface and power management. The observer will monitor the real power, reactive power, voltage level, frequency and phase sequence. These functions are mandatory and it must be incorporated in the controller in order to connect the distributed energy system with the grid.

1.3.2 Sources of MicroGrid

The main benefit of the MicroGrid is that it should use electricity, which is generated locally and matches the load requirements in the MicroGrid. There are several types of MicroGrid resources that can be considered as photovoltaic cells, fuel cells, wind energy, energy storage devices, etc. To reduce the environmental impact and to improve the energy efficiency the research will help to reach the goal. The costs of renewable energy sources have reduced significantly over the past decades and should continue to drop in the future. Moreover, to combine the benefits of RES and to obtain clean, reliable, efficient supply of power, the so-called hybrid power systems are integrated into various structures. Climate, geography and availability of fuel in the region decides the structure of hybrid system with
various combinations of sources. An outline of the various renewable energy sources is given below.

1.3.2.1 Photovoltaic cell

The solar energy is converted into electrical energy by using solar cells (PV cells). A solar cell is generally made from semiconductor materials such as crystalline silicon and absorbs sunlight and produces electricity through a process called the photovoltaic (PV) effect. The efficiency of PV cell is typically around 10% - 15% and it is calculated through its ability to convert available sunlight into electrical energy that can be used. Therefore, to produce a lot of electric power, the PV cell must have a bulky surface area. Individual solar cells are generally manufactured and assembled in modules consisting of 36 to 72 cells, depending on the output voltage and current. The size of the PV modules varies in size and it is usually between 0.5 m$^2$ to 1 m$^2$, and generate approximate power of 100 W/m$^2$ (Blaabjerg et al. 2013).

Figure 1.5 shows the formation of PV array of PV cells. For the PV system, the output voltage is a DC and its magnitude depends on the configuration of cells / solar modules. On the other hand, the output current of the PV system depends mainly on the solar radiation available. The power electronics interface is used in photovoltaic systems to convert the generated DC voltage into AC voltage, which is suitable for consumer use and grid. In general, before converting into AC, the DC voltage generated by the PV cell / array is boosted to a higher value by using DC-DC converters. The controller should control the output voltage and current according to the requirement irrespective of weather conditions.
The Maximum Power Point Tracking (MPPT) technique is used to extract the maximum energy from a PV array under different conditions. The MPPT is used to control voltage on the DC-DC converter and the inverter are used to control the grid current. The PV system can be installed anywhere, where there is solar irradiation of any intensity. This means that a large potential for installation on roofs and facades of private and public buildings, and can be easily incorporated into the architecture of the buildings, which is essential for a distributed generation based electricity system in large urban areas.

The PV systems can be designed into several configurations. In each configuration, the PEI is used to interconnect the PV module and the grid. The most common type of PV system is shown in Figure 1.6, in which the centralized inverter is used.
The PV modules are connected as an array and connected to the grid through DC-AC converter. The main advantage of this system is the low cost because of only one inverter. The main drawbacks of this design are that the power loss is high in blocking diode and less reliable, because if there is any fault in the inverter then the whole system will be out of service.

Figure 1.7 shows the arrangement of string-array PV system. The PV panels are connected in series to form a string and they are connected to the grid through an inverter. The inverter is connected to each string. The main advantages of this structure are that the power loss is low in blocking diodes and MPPT can be applied to each string. The drawback of this topology is the increase in cost due to number of inverters.
In the above said structures, there is no need of DC-DC converters, because the high voltage is obtained by connecting large number of panels in series. Hence the cost of the panels is high. In order to reduce the cost of panels, the number of panels connected in series is reduced and a DC-DC converter is connected in between the string and inverter to increase the voltage level as shown in Figure 1.8.
Figure 1.9 shows a configuration where each PV module has its own converter and inverter. In some cases, the DC-DC converter is not used and it consists of only inverter called as microinverter. The main advantage of this system is that the more PV modules can be added into the system, because each module has its own PEI. The reliability of the system is increased, because if there is any fault in a string, then that particular string can be disconnected from the grid and there is no interrupt in the supply. But the cost of the system is high because of the number of converters and/or inverters. It is a highly flexible and configurable structure. The PEI is usually mounted with the PV panel itself and it can be used as a plug-in device.

The most generalized form of PEI in PV system is the DC-DC converter followed by inverter and it is shown in Figure 1.10. The voltage from the PV string is first boosted by using a DC-DC converter and it is converted into grid compatible AC and connected to the utility.

![Figure 1.9 PV system with Microinverters](image)
1.3.2.2 Fuel cell

Fuel cells are currently being developed that can be used as substitutes for ICE vehicles and stationary applications for electric power generation. The fuel cell is an electrochemical device that produces electricity directly. Fuel cells have important advantages like, low emission of greenhouse gases and high-energy density. The energy density of a typical Fuel Cell (FC) is 200W/litre, which is nearly ten times the battery (Frede Blaabjerg et al. 2004). The typical efficiency of a Fuel Cell is in the range of 40% to 60%. If the heat generated by the fuel cell is used for co-generation, then the overall efficiency of a FC system can be as high as 80% (Frede Blaabjerg et al. 2004).

Fuel cells can be classified into five different categories based on the electrolyte: Proton Exchange Membrane Fuel Cell (PEMFC), Solid-Oxide Fuel Cell (SOFC), Molten Carbonate Fuel Cell (MCFC), Phosphoric Acid Fuel Cell (PAFC) and Aqueous Alkaline Fuel Cell (AAFC). The PEMFC type fuel cell is a fast-growing source of primary energy in the portable power supply and distributed generation, due to the high energy density, low operating temperature and simple structure (Haiping Xu et al. 2004). The basic configuration of the PEMFC is shown in Figure 1.11. For PEM fuel cell, hydrogen and oxygen gases are fed into the fuel cell. The anode conducts electrons those are released from hydrogen molecules. The cathode transports the electrons back from the external circuit to the catalyst, where it combines...
with the hydrogen and oxygen ions to form water, which is the by-product of the FC. The electrolyte is the proton exchange membrane, which allows positively charged ions, blocks the flow of electrons. The catalyst is porous and made up of carbon paper or cloth and it is coated with platinum powder. The reaction described is carried out in a cell, resulting in cell potential of 0.7 volt approximately. Multiple cells may be placed in series, often referred to as a stack to increase the output DC voltage.

Fuel cells are similar to PV systems as they produce DC power. Power Electronic interfaces like inverters and DC-DC converters are required to convert the generated low DC voltage to high DC/AC voltage in order to supply the electric power to the consumer or to the grid. The simplest structure of FC system configuration is shown in Figure 1.12. Here only one DC-AC converter is used. If the generated voltage is low, then the low voltage is increased to high voltage by means of a transformer. The transformer also provides isolation between the system and the grid. The main drawbacks of this configuration are that the transformer used at the supply frequency is very large and expensive.

Figure 1.11  Basic configuration of PEMFC
(Source: Farret & Simoes 2006)
In order to reduce the cost and size of the FC system, the DC-DC converter is used to increase the DC voltage level, hence the transformer is not necessary. The structure is shown in Figure 1.13. The DC-DC converter is also used to provide isolation between the grid and the FC system.

Another configuration of the FC system is shown in Figure 1.14, which consists of high frequency link between the two converters. The low DC voltage is converted into a high frequency AC voltage. Then an AC-AC converter is used to convert the high frequency AC voltage to supply frequency AC voltage. By using a high frequency AC link, the cost and size of the transformer are greatly reduced.

The power electronics interface for FC systems are varied and it is based on number and types of stages in the conversion. The mostly used PEI for FC systems are DC-DC converter followed by DC-AC converter and DC-AC converter followed by AC-AC converter. In general, the low DC voltage is boosted by means of DC-DC converter and the isolation between the FC
and inverter is also provided. The power flow between the source and the utility grid and power factor are controlled by the DC-AC converter.

![Figure 1.14 Fuel cell system with high-frequency AC link](image)

1.3.2.3 Wind energy

Wind turbines convert the kinetic energy of wind into mechanical energy and it can be converted into electrical energy by a generator. The electrical energy is typically generated either by an induction generator or by a synchronous generator. The output power is typically between 10 kW and 2.5 MW. The wind energy was captured using a blade which is connected to the rotor of a generator. The schematic of a wind turbine and its components are shown in Figure 1.15. In the last two decades, wind energy has developed and it has been widely accepted as a power generation technology. Due to the growth of the wind turbine market globally, the wind energy is playing an important role in electric power generation (Farret & Simoes 2006).

The main components of a typical wind energy conversion system are demonstrated in Figure 1.16, including the turbine, gear arrangement, generator, power transformer and power electronics interface (Chen & Blaabjerg 2006). Wind energy technology can be divided into three categories: Wind Energy Conversion Systems (WECS) without power electronics interface, WECS with the partly power electronics interface and WECS with the full power electronics interface.
Systems without power electronics interface uses an induction generator to convert wind energy to electrical energy. The structure of this configuration is shown in Figure 1.17. The wind turbine rotates the rotor shaft of an induction generator and its stator is connected directly to the grid without any power electronics interface.
Figure 1.17 WECS without PEI

This wind turbine must be operated at a constant speed and the rotor speed is adjusted by controlling the pitch of the blades of wind turbines. The induction machine requires reactive power to generate electric power, which can be supplied from the grid or external capacitors.

WECS with partly power electronics interface requires a wound rotor induction machine which operates as a Double Fed Induction Generator (DFIG). The power generated in the wound rotor is collected by using slip rings and it connects to the grid through the power electronic interface as shown in Figure 1.18. This configuration provides variable speed operation. If the DFIG is running at super-synchronous speed, then both the stator and rotor deliver power to the utility grid. If the DFIG is running at sub-synchronous speed, then the rotor alone supplies power to the utility grid.

Figure 1.18 WECS with partly PEI
The WECS with the full power electronic interface is used in large-scale wind power generation (Juan Manuel Carrasco et al. 2006) and it is shown in Figure 1.19.

![Wind Energy Conversion System Diagram](image)

**Figure 1.19 WECS with full PEI**

The generation system uses a synchronous generator or a permanent magnet synchronous generator for converting the wind turbine power to a variable voltage, variable frequency output that varies with the wind speed. A power electronics based rectifier and inverter is used to convert the variable voltage, variable frequency output to a rated voltage at rated frequency. The rectifier consists of both bridge rectifier and boost converter. The variable AC voltage with variable frequency is first rectified and boosted to obtain a fixed DC voltage at high level. Then it is converted into AC voltage at rated frequency. If the AC voltage is not up to the grid voltage, then it is stepped-up by using a transformer before supplying power to the grid. This system has additional losses in the power conversion system. This system allows the wind turbine to operate in a variable speed mode, allowing more wind energy to be captured and converted. The main drawback of this configuration is that the control of PEI is more complex.

### 1.3.2.4 Energy storage devices

Larger generators are operating at rated capacity at all times to increase the generating system efficiency. During a typical daily load cycle, the loads utilized by the customer vary. At peak load, additional low-capacity
generators are operated in the system and it will be added to the grid in order to support the increased load. The cost of running the low-capacity generators are high. Therefore, the energy storage systems are used to store the excessive energy generated from the large generators during low load period. This stored energy can be supplied into the grid during peak load period. In fact, in their own generation in a distributed system, normally renewable energy sources have the capability to store energy. The stored energy can be used to provide power during high demand.

There are a variety of technologies used to store energy in the electric power system. They are batteries, Superconducting Magnetic Energy Storage (SMES), flywheels, ultra-capacitors, Compressed Air Energy Storage (CAES), pumped hydro and production of hydrogen gas and it is stored to run the fuel cells or hydrogen IC engines. Batteries and flywheels are commonly integrated at the distribution system level because they are commercially available. Battery banks connected to the grid are generally either lead-acid or flow batteries. Lead-acid, Nickel-Cadmium (NiCd), Nickel-Metal Hydride (NiMH), and Lithium ion batteries are the most commonly used in low voltage consumer electronics.

The basic and simplest configuration of Battery Based Energy Storage System (BESS) is shown in Figure 1.20. It consists of battery bank followed by a single DC-AC converter and the isolation are obtained by using transformer between the inverter and the grid. The main drawback of this system is the size and cost of the low frequency transformer.

In order to replace the transformer, the DC-DC converter is used in the input stage as shown in Figure 1.21. The DC-DC converter must have bidirectional power flow capability, so that the battery will charge from the grid or discharge to the grid through the same converter (Ponnaluri et al. 2005).
When the battery is charging, the DC-DC converter maintains the constant voltage at the battery terminals. The controller regulates the input voltage of the DC-DC converter from the inverter in order to maintain a constant voltage for charging. During discharging mode, the DC-DC converter maintains the constant voltage at its output, in order to obtain the regulated AC voltage at the inverter output. The inverter controls active power during charging of battery and both active and reactive power during the discharge process.

**Figure 1.20** Battery based energy storage system with single inverter

**Figure 1.21** Battery based energy storage system with bidirectional converter and inverter
Flywheels are very popular energy storage device due to the simplicity of storing kinetic energy in a spinning mass. Flywheel Energy Storage System (FESS) converts kinetic to electric energy and it is accomplished by electromechanical machines. Many different types of generator machines are used in flywheel systems, such as permanent magnet machines, induction machines, and switched reluctance machines (da Silva et al. 2003). When the generated power is higher than the load demand, then the difference between them is stored in the flywheel driven by electric machines. In this case the electric machine will operate as a motor. On the other hand, when a power fluctuation is detected in loads, the additional power required is supplied by the flywheel and it drives the electric machine as a generator to provide additional power. The simplest form of FESS configuration is as shown in Figure 1.22. In case of FESS, the generator and the grid are interconnected by means of back- back converter (Lazarewicz & Rojas 2004). The variable frequency AC output of the flywheel generator is first converted to DC power. Then the DC power is converted into AC power by means of DC-AC converter in order to supply the power to consumers or grid.

![Flywheel based energy storage system with back-to-back converter](image)

**Figure 1.22 Flywheel based energy storage system with back-to-back converter**

During charging, the grid-side converter works as a rectifier while the generator-side converter works as an inverter. During discharge, the grid-side converter works as rectifier and the generator-side converter works as an inverter.
Batteries, Ultra-Capacitors, Fuel Cells and Solar panels are built using low voltage cells (in the range of 0.5V to 4V). These cells are connected in series to achieve a reasonable voltage for application. However, the connection of a large number of cells in series increases complexity, and reduces system performance because of differences between cells (e.g., variations in manufacturing) and different operating conditions (e.g. temperature of the cell). It is also important to note that these sources or storage devices show significant variation in the output voltage depending on factors such as the state of art in the case of charging batteries and solar radiation intensity in the case of solar panels. In typical domestic or industrial applications such as electric motor drives and grid, utility, it is usually necessary or desirable to use a stable and relatively high voltage. As this is the case, a boost converter can be used to raise the source voltage to the level specified for the application and produce a stable voltage despite variations in the input voltage source.

Figure 1.23 shows the system being studied, especially the DC-DC converter which is the focus of this work. The system comprises a renewable energy source, which is connected to a DC-DC converter that adjusts the voltage supplied to the DC-AC converter. The inverter can provide the desired amount of power for local load connected to its terminals or to the distribution network via a relay.

Figure 1.23 Proposed system
1.4 OBJECTIVES

The aim of this study is to analyze, design and implement a DC-DC converter that connects a distributed energy resource and a distribution network. This dissertation explores topologies that can be used to raise the voltage, especially when high voltage gain is needed. It should be noted the difference between the features “high static gain” and “wide range”. The static gain of a converter is defined as the relationship between output voltage and converter input voltage in steady state, and broad working range is related to how the static gain can vary, maintaining the correct operation of the system.

The converters with high boosting capability, high efficiency and high power density are necessary to improve system performance and reduce system cost. The main objectives of this thesis are:

a. To propose new power electronic converters that can step up the low input-voltage to high output-voltage. Three topologies with single power switch are presented:

   i. Hybrid Switched Inductor Capacitor converter: This converter is constructed by using Switched Inductor (SI), Switched Capacitor (SC) and Voltage Multiplier (VM) cells.

   ii. Hybrid Voltage Lifted Switched Inductor Capacitor converter: This converter is constructed by using voltage lifted SI, SC and VM cells.

   iii. Hybrid Voltage Lifted Switched Coupled Inductor Capacitor converter: This converter is constructed by
using voltage lifted switched coupled inductor, SC and VM cells.

b. To reduce the voltage stress on semiconductor devices.

c. To develop a complete set of mathematical design equations for the proposed converters to allow selection of their components based on the desired voltage and power rating.

d. To investigate their characteristics and to confirm their feasibility with experimental work obtained from prototype converters.

Finally, the specifications of the converter in this research for illustration purpose are given in Table 1.2.

**Table 2 Specifications of the converters to be designed**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output power, $P_O$</td>
<td>500 W</td>
</tr>
<tr>
<td>Input voltage, $V_{in}$</td>
<td>24 V</td>
</tr>
<tr>
<td>Input voltage variation, $\Delta V_{in}$</td>
<td>± 33.33%</td>
</tr>
<tr>
<td>Output voltage, $V_O$</td>
<td>360 V</td>
</tr>
<tr>
<td>Load resistance, $R_O$</td>
<td>260 Ω</td>
</tr>
<tr>
<td>Switching frequency, $f_s$</td>
<td>100 kHz</td>
</tr>
<tr>
<td>Input current ripple, $\Delta I_{in}$</td>
<td>20%</td>
</tr>
<tr>
<td>Output voltage ripple, $\Delta V_O$</td>
<td>1 %</td>
</tr>
</tbody>
</table>

**1.5 THESIS OUTLINE**

In Chapter 1, the research background is presented. The basic concepts of the Distributed Generation and MicroGrid are given. The advantages and disadvantages of the DG and MG are also provided. The distributed energy sources, power electronic interfaces are introduced.
In Chapter 2, an overview of non-isolated dc-dc converters with high step-up gain are reviewed for renewable energy applications. The converters are classified into five categories and each category is analyzed in terms of efficiency, cost, size and voltage stress across the semiconductor devices.

In Chapter 3, a new high step-up dc-dc converter will be introduced. This converter is constructed by using the switched inductor-capacitor cell. In this chapter, the operating principle, topological modes, theoretical waveforms, detailed analysis, simulation and experimental results are presented.

In Chapter 4, a derivative of the converter proposed in Chapter 3 is presented. The new topology is obtained by replacing the switched inductor with voltage lifted switched inductor. It also explains the operating principle with topological modes of the converter and analysis of the steady state characteristics. The simulated and experimental waveforms are shown to support the described principles and analysis.

Chapter 5 shows the circuit configuration of the proposed high step-up converter with coupled inductors. The coupled inductors are used to increase the voltage gain without increasing the component count. The principle of operation is described in detail. The steady state analysis of the converter with key waveforms, simulated and experimental waveforms are presented.

Chapter 6 gives the conclusions of this thesis, and recommends future research for the further improvements on high step-up converter for MicroGrid applications.