CHAPTER 1
INTRODUCTION

1.1 INTRODUCTION TO MICROGRID

A microgrid is a portion of the power system that comprises distributed generation, energy storage and interconnected loads. Microgrid has the capability to meet its own load’s demand from local generating sources that helps in reducing the demand on the main grid and it has greater flexibility. The microgrid can be operated in parallel with the main grid or in islanding mode. The microgrid has the potential to provide a highly reliable system and has the capacity to recover quickly from the grid disturbances. Microgrid should be robust in controlling the voltage and frequency and should protect the network and equipment connected to the microgrid.

The important aspects of the main electricity grid are efficiency and reliability which are enhanced by introducing the microgrid concept. Microgrid can be constructed by using solar PV or wind or hybrid generation system. PV based microgrid must be efficient and should provide reliable power when it is interconnected with the main grid or when operated in island mode (Abdelsalam et al 2011). Hence, the PV based microgrid requires the generated power from PV system need to be maximized, for which the PV system is necessary to operate at its maximum power point (MPP). To extract maximum power from the PV system, maximum power point tracking (MPPT) controller is used in the PV system. To design proper MPPT controller, the information about the PV module’s maximum power at MPP
under varying environmental conditions such as irradiation and temperature is needed (Ishaque et al 2011a). The output power from the PV based microgrid can be exactly predicted by finding the PV modules’ output power through simulation under varying environmental conditions, which requires accurate estimation of the parameters in the PV model.

Recently, microgrids are developed based on renewable energy sources and it will be connected with the future power systems due to its large advantages such as flexible electricity supply, more energy savings and less environmental impact. This creates numerous research interests to work on renewable energy sources based microgrid, since it can provide reliable, resilient and high quality efficient power to the end users. The renewable energy sources generate uncontrollable power that varies with the environmental conditions and hence, they need power electronic controller for regulating their output when they are connected with the microgrid or operating as standalone systems.

The major issues in the microgrid operation are reliability, stability, congestion management, power flow control, power quality, protection system and integration of more distributed generators (DGs) (Anil kumar et al 2013). The technical challenges of the microgrid are power flow control between generation side and distributed load side and power quality problem that arises due to power electronics controllers. Prediction of the power generation from the renewable energy sources is a difficult task because the availability of them varies according to the environmental conditions. The microgrid needs protection and stable operation when it is operated in both grid connected mode and islanded mode (Buigues et al 2013).

The major advantages of microgrid are enhancement in energy efficiency, minimisation of the overall energy consumption, enhanced
reliability and power quality, and also it can be operated as a single collective load within the power system (Priolkar & Shet 2013). The disadvantages of microgrid are weak energy storage capabilities, limited information on the true total cost of operation and the associated payback periods. Microgrid provides various benefits to end users and utilities. Various benefits includes reduction of greenhouse gas emissions due to the usage of renewable energy sources, power quality enhancement, local power production, reduction in the power transmission and distribution losses and reasonable electricity price in remote areas. The distributed generation (DG) comprises of solar photovoltaic, solar thermal, wind, biomass, fuel cell and micro turbines and its role is important for microgrid enhancement. The architecture of microgrid is shown in Figure 1.1.

![Figure 1.1 Architecture of microgrid](image)
1.2 INTRODUCTION TO RENEWABLE ENERGY

The rapidly decreasing reserves of fossil fuels in the world and the pollution associated with the combustion of fossil fuels lead to the usage of more amount of renewable energy sources such as sunlight, wind, tides and geothermal heat in the present scenario. The renewable energy sources are much cleaner and produce energy without the emission of harmful gases such as carbon dioxide, nitrous oxide and sulphur hexafluoride, etc.

In 2050, the world’s energy demand is expected to be doubled and at the end of the present century, the energy demand will be tripled. The power generation from the presently available power stations is inadequate to supply this demand in a sustainable way. In future, the renewable energy sources will provide more contribution to supply the part of energy demand and it is a frightening challenge for engineers, scientists and power producers to fulfil the demand. The power from the sun at the top of the atmosphere is $1,70,000$ TW and the amount of energy received from the sun in one hour is $4.3 \times 10^{20}$ J. But worldwide, the annual consumption of energy is only $4.1 \times 10^{20}$ J (Lewis & Crabtree 2005).

The contribution of power generated from solar energy around the world is less than $0.1\%$ of the total world electricity generation (Lewis & Crabtree 2005). However, photovoltaic (PV) power is economical for few applications. These applications include satellites, power distribution infrastructure lacking area, and remote areas where running distribution lines is not practical. PV system applications are economically feasible when the cost of PV system drops, which is taking place now due to reduction in the cost of the PV module. The market price of PV cells has decreased from US $76.67/W_p$ in the year 1977 to $0.36/W_p$ in the year 2014 as shown in Figure 1.2 (Wikipedia). Even though conventional generating systems are
more economical, PV power is a more attractive choice for future considering its non-polluting nature.

**Figure 1.2 Price list of PV cell in $ per Watt**

The huge gap between available energy in earth from the sun and our present use of solar energy has motivated to do more research work on solar power generation. Presently, the significant contributors of the primary energy supply are fossil fuel, nuclear power and solar power. In the year 2035, power generation from the solar energy will be competitive to the fossil fuel as a primary source (Lewis & Crabtree 2005).

### 1.2.1 World PV Energy Scenario

Solar energy is the most abundant energy resource and it is available for use in its direct (solar radiation) and indirect (wind, biomass, hydro, ocean etc.) forms. About 60% of the total energy emitted by the sun
reaches the Earth’s surface. Even if only 0.1% of this energy could be converted at an efficiency of 10%, it would be nearly four times larger than the total world’s electricity installed capacity (WER 2013).

<table>
<thead>
<tr>
<th>Year</th>
<th>Power in MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>1,288</td>
</tr>
<tr>
<td>2001</td>
<td>1,615</td>
</tr>
<tr>
<td>2002</td>
<td>2,069</td>
</tr>
<tr>
<td>2003</td>
<td>2,648</td>
</tr>
<tr>
<td>2004</td>
<td>3,723</td>
</tr>
<tr>
<td>2005</td>
<td>5,112</td>
</tr>
<tr>
<td>2006</td>
<td>6,660</td>
</tr>
<tr>
<td>2007</td>
<td>7,191</td>
</tr>
<tr>
<td>2008</td>
<td>15,844</td>
</tr>
<tr>
<td>2009</td>
<td>23,182</td>
</tr>
<tr>
<td>2010</td>
<td>40,536</td>
</tr>
<tr>
<td>2011</td>
<td>70,469</td>
</tr>
<tr>
<td>2012</td>
<td>1,011,411</td>
</tr>
<tr>
<td>2013</td>
<td>1,388,56</td>
</tr>
</tbody>
</table>

*Figure 1.3 Cumulative global PV installed capacity*

Cumulative global renewable electricity installed capacity has grown by 97% from 2000 to 2012 (from 748 GW to 1,470 GW) (NREL 2012). During the year 2013, 22.1% of the global electricity is produced from the renewable energy. Cumulative global installed renewable energy capacity is 1560 GW in the year 2013 (REN21 2014). Worldwide, the installed PV capacity from the year 2000 to 2013 is shown in Figure 1.3 which shows the continuous increase in the installed PV capacity and is nearly 139 GW at the end of year 2013. In the year 2013, the newly added PV installed capacity was 39 GW (EPIA 2014).

### 1.2.2 Indian PV Energy Scenario

In India, the total installed capacity of power stations is 254049.49 MW as shown in figure 1.4 but the available power is 118762.50 MW and the power demand in India is 123809.72 MW as on 31.09.2014. Therefore to meet
the present power demand, India should generate more than 5047.22 MW power. So far, all over India, 25,722 villages are not electrified as on 31.05.2014. The installed capacity of power from renewable energy sources is 31692 MW in India (CEA 2014). The country has the solar power installation capacity of over 2.517 GW as on May 2014. In the year 2013 alone, PV based installation capacity of 1.1GW is newly added.

![Figure 1.4 Overall power installed capacity in India](image)

1.3  INTRODUCTION TO PHOTOVOLTAIC SYSTEM

1.3.1  Photovoltaic Cell Working Principle

A solar cell is an electronic device which directly converts sunlight into electricity. PV cells are made by n-type semiconductor material and p-type semiconductor material. Crystalline silicon PV cell consists of seven layers such as transparent adhesive, protective glass cover, antireflective coating, n layer, p layer and two electrical contacts.

When sunlight strikes on the photovoltaic (PV) cell surface, it produces both current and voltage to generate electric power. Impurities such
as boron or phosphorus are added to the semiconductor material. These impurities create free electrons when light falls on the PV cell. These free electrons flow from the n layer through the electrical load and reach the p layer which produces electric power. This process is called as photovoltaic effect. In Figure 1.5, the basic component of a PV cell is demonstrated.

Figure 1.5 Basic components of crystalline silicon PV cell

In 1839, this photovoltaic effect was invented by a French scientist Edmund Becquerel, who found that certain semiconductor materials would generate small amount of electric power when light strikes the particular materials (Hersch & Zweibel 1982). In 1954, the first photovoltaic module was manufactured in the Bell laboratories in the United States and it has low conversion efficiency of 4.5%. In 1960s, for space applications the power was drawn from the photovoltaic systems and it leads to improve the reliability and reduce the cost abruptly. During the energy crisis in the 1970s, the power generation from the photovoltaic systems is enhanced to fulfil the required power for non-space applications. The photovoltaic systems are simple in design and rugged in nature such that they are not affected by varying
environmental conditions and they need very little maintenance. As standalone system, the photovoltaic system provides power in the range of microwatts to megawatts and also, it provides power in megawatts for large scale power utility system.

In 1980, the energy payback period of photovoltaic module is 1 to 4 years, and it depends on the type of PV module, location and peak power of the PV module. Today, the payback period of PV module made by the crystalline silicon is 1 to 2 years. The life time of PV module is increased from 25 to 30 years and simultaneously the silicon material usage for production of PV cell is reduced during the last 5 years from 16g/W to 6g/W due to increased efficiencies and thinner wafers (Fraunhofer 2014). Multi junction thin-film concentrating PV system’s payback period is reduced to less than one year. The present market price of PV modules are US $2.5/W to $4/W which is cost-effective for household applications but for larger PV systems, the cost of PV module is further reduced to less than US $2/W which is cost-effective for grid connected applications (WER 2013).

1.3.2 PV Cell, PV Module and PV Array

A photovoltaic cell is the building block of a PV module. Most of the PV cells are made from silicon doped with very small quantities of boron, phosphorous, gallium, arsenic, or other materials. PV Cell is formed by p-n junction diode that converts sunlight into direct current (DC) electricity when the PV cell is illuminated. In Figure 1.6, the PV module is made by connecting more number of PV cells (at least 36 cells) in series. A typical PV module may have 36, 54, 60, 72 or 96 cells in series.

Single photovoltaic cell produces power of less than 3 watts and voltage of approximately 0.5 to 0.6 volt DC. Since each PV cell voltage is less than 0.6V, more number of PV cells is connected in series in the PV module to
achieve the required output voltage. The current remains the same and the total voltage is sum of the individual PV cell voltages in the PV module. The $I$-$V$ characteristics curves for PV module having different number of PV cells connected in series are shown in Figure 1.7.

![Figure 1.6 A typical PV module formed by 36 PV cells connected in series](image1)

**Figure 1.6** A typical PV module formed by 36 PV cells connected in series

![Figure 1.7 I-V characteristics curve for PV module having different number of PV cells connected in series](image2)

**Figure 1.7** $I$-$V$ characteristics curve for PV module having different number of PV cells connected in series

The $I$-$V$ characteristics curve when more than one PV modules are connected in series is shown in Figure 1.8.
Figure 1.8  *I-V* characteristics curve when 2 or 3 PV modules are connected in series

In parallel connection of PV modules, the voltage remains the same and the total current is sum of the individual PV module current. A typical *I-V* characteristics curve when more than one PV modules are connected in parallel is shown in Figure 1.9.

Figure 1.9  *I-V* characteristics curve for 2 or 3 PV modules connected in parallel
When two or more PV modules are connected in series, it is referred as a PV panel or PV string and is shown in Figure 1.8. When two or more PV strings are connected in parallel with each other, it is referred as a PV array and is shown in Figure 1.10. PV string can be used either individually or in parallel connection with the other strings to enhance the voltage/current further for high-power applications.

1.3.3 Effect of Bypass Diode

Bypass diode is like a freewheeling diode and it is connected across the individual PV cell or PV module which provides a current path whenever fault occurs in the PV cell or PV module. Bypass diodes are connected in reverse bias between the PV cells or PV modules as shown in Figure 1.10 and it has no effect on the cell or module’s output. Under shaded conditions such as cloud, dirt and tree shadows, the shaded PV modules act as load instead of generator and it leads to hot spot problem in the PV module. The bypass diode eliminates this problem, by diverting the generated current of non-shaded PV modules not to flow through the shaded modules.

1.3.4 Effect of Blocking Diode

Blocking diodes are connected in series with the PV modules as shown in Figure 1.10 and it is used to prevent the current flow back into the PV module/array. Physically there is no difference between bypass diode and blocking diode but if they are connected differently then it will serve different purpose. Blocking diode prevents the current generated by the other parallel connected PV modules in the same array flowing back through a shaded PV module/array and also to prevent the fully charged batteries from discharging.
through the PV array. Hence, blocking diodes should be used in each parallel connected branch when several PV modules are connected in parallel.

Figure 1.10 PV array with bypass diode and blocking diode

1.4 OVERVIEW OF PHOTOVOLTAIC TECHNOLOGIES

PV modules are made by various semiconductor materials. The PV module technologies are broadly classified into crystalline silicon and thin-film based technology.

The crystalline PV technology is further classified as follows:

- Mono-crystalline or single crystalline
- Multi-crystalline or poly-crystalline
- Ribbon sheets

The thin-film PV technology is classified as follows:

- Amorphous silicon (a-Si)
- Cadmium telluride (CdTe).
- Copper Indium gallium Diselenide (CIGS)
- Multi junction cells (a-Si/m-Si)

Crystalline silicon and thin-film are the leading semiconducting materials used for the production of different PV technologies. The PV cell characteristics vary depending on the absorption capability of sunlight, conversion efficiency, manufacturing technology and production cost. Worldwide, the contribution of crystalline silicon in the production of PV module is 91% (36% by mono-crystalline, 55% by poly-crystalline) and remaining 9% share is from thin-film (5% CdTe, 2% a-Si and 2% CIGS) technologies in year 2013. In the past 10 years, the average efficiency of the commercial wafer-based silicon PV modules is increased from 12% to 16% and at the same time, the efficiency of the CdTe PV module is increased from 9% to 13% (Fraunhofer 2014). In the laboratory, the efficiency of the high concentration multi-junction PV cells reaches up to 44.7%. The recent concentrator technology improves the PV module efficiencies up to 36.7%. During the year 2013, the PV module’s total production based on Si-wafer PV technology accounted for about 90%. The performance ratio of PV module is the ratio of the actual energy output and theoretical energy output and it is used to evaluate the efficiency of a PV plant. In the year 2000, the performance ratio was about 70%, but now the performance ratio is improved around 80% to 90% (Fraunhofer 2014).

1.4.1 Crystalline Silicon

Worldwide, the silicon semiconductor material is the second most abundant element on earth after oxygen. Worldwide, the market share of crystalline silicon in the production of PV module is 90%. For these reasons, PV technologies based on crystalline silicon have dominated the PV terrestrial market for several decades and are still dominant. The single crystalline silicon PV module’s efficiency varies from 17% to 21%. Performance and
reliability of the crystalline silicon PV technology are continuously improved that helps to decrease the cost of this technology. In 1980s, low cost polycrystalline silicon wafers were developed for alternative to the single crystalline silicon, but the efficiency of polycrystalline silicon technology is slightly lower. The efficiency of the poly-crystalline PV modules may vary from 14% to 16% (SunShot 2012). In the laboratory, the efficiency of the mono-crystalline and poly-crystalline PV module is 25% and 20.4% respectively (Fraunhofer 2014).

1.4.2 Thin-film Technologies

Thin-film technologies are made by using more number of thin layers of semiconductors approximately 100 times thinner than those used in conventional mono and poly-crystalline silicon technologies. The absorption coefficient of thin-film technologies is higher than the crystalline silicon that induced to use lesser materials and low cost technologies. The main technical challenge for thin-film technologies is to improve the PV module efficiency with reduced size. Fabrication process is relatively simple compared with the crystalline silicon that leads to further reduction of cost of this technology and its efficiency varies between 5% and 8%. The highest laboratory PV cell efficiency of the thin-film technology is 19.8% for CIGS, 19.6% for CdTe and 13.4% for amorphous silicon. In the year 2013, the annual production of solar power by CdTe thin-film technology is around 2 GW globally and the market share of all thin-film technologies increases to around 10% of the total annual solar power production globally (Fraunhofer 2014).

1.4.3 Crystalline PV cell versus Thin-film PV cell

Advantages of crystalline silicon PV cell are as follows:

- High efficiency
- High stability
• Fabrication process is simple
• High reliability and long endurance
• High resistance to heat and lower installation costs
• Silicon is more environment friendly
• Single crystal panel can withstand the harsh conditions associated with space travel

Disadvantages of crystalline silicon PV cell are as follows:
• Initial cost of solar photovoltaic components are more expensive
• It has low absorption coefficient, rigid and can be easily broken

Advantages of thin-film PV cell are as follows:
• Less expensive
• Thin wafer sheets, more flexible and easy to handle
• Possibility of breakages is less

Disadvantages of thin-film PV cell are as follows:
• Low efficiency
• More complex structure

1.4.4 Laboratory and Commercial Efficiency for Different PV Cell Types

In the research laboratory, the recorded efficiency of the single crystalline PV cell is about 26.4%, and multi-crystalline PV cell efficiency is about 20.4% and thin-film amorphous PV cell is about 13.4% (Ciulla et al 2014). Multi junction concentrator PV cell reaches the highest efficiency in the research laboratory compared with any kind of PV cell types. Multi junction concentrator PV cell has several numbers of p-n junctions and each p-n junction absorbs different wavelength of sunlight which increases the efficiency of the PV cells. Single junction GaAs PV cells have high withstanding capability against the damage due to radiation effect. Table 1.1
shows the research laboratory efficiency of different PV cell types (Ciulla et al 2014).

### Table 1.1 Research Laboratory efficiency of different PV cell types

<table>
<thead>
<tr>
<th>Type</th>
<th>Classification</th>
<th>Cell Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi-junction cells (2-terminal</td>
<td>Four junction or more (no concentrator)</td>
<td>37.80</td>
</tr>
<tr>
<td>monolithic)</td>
<td>Three junction (concentrator)</td>
<td>44.00</td>
</tr>
<tr>
<td></td>
<td>Three junction (no concentrator)</td>
<td>37.70</td>
</tr>
<tr>
<td></td>
<td>Two junction (concentrator)</td>
<td>32.60</td>
</tr>
<tr>
<td></td>
<td>Two junction (no concentrator)</td>
<td>30.80</td>
</tr>
<tr>
<td>Single junction GaAs</td>
<td>Concentrator</td>
<td>29.10</td>
</tr>
<tr>
<td></td>
<td>Thin-film crystal</td>
<td>28.80</td>
</tr>
<tr>
<td></td>
<td>Single crystal</td>
<td>26.40</td>
</tr>
<tr>
<td></td>
<td>Single crystal</td>
<td>27.10</td>
</tr>
<tr>
<td></td>
<td>Thin-film crystal</td>
<td>20.10</td>
</tr>
<tr>
<td>Crystalline Si cells</td>
<td>Silicon hetero structures (HIT)</td>
<td>24.70</td>
</tr>
<tr>
<td></td>
<td>Multi-crystalline</td>
<td>20.40</td>
</tr>
<tr>
<td></td>
<td>Thick Si film</td>
<td>16.00</td>
</tr>
<tr>
<td></td>
<td>Cu (In,Ge)Se2</td>
<td>20.40</td>
</tr>
<tr>
<td>Thin-film technologies</td>
<td>CdTe</td>
<td>18.70</td>
</tr>
<tr>
<td></td>
<td>Nano-micro-poly-Si</td>
<td>17.20</td>
</tr>
<tr>
<td></td>
<td>Multi-junction poly-crystalline</td>
<td>15.00</td>
</tr>
<tr>
<td></td>
<td>Amorphous SiH (stabilized)</td>
<td>13.40</td>
</tr>
<tr>
<td>Emerging photovoltaic</td>
<td>Dye-sensitized cells</td>
<td>11.40</td>
</tr>
<tr>
<td></td>
<td>Organic cells</td>
<td>11.10</td>
</tr>
<tr>
<td></td>
<td>Inorganic cells</td>
<td>11.10</td>
</tr>
<tr>
<td></td>
<td>Organic tandem cells</td>
<td>12.00</td>
</tr>
<tr>
<td></td>
<td>Quantum dot cells</td>
<td>7.00</td>
</tr>
</tbody>
</table>

PV modules are made by different PV technologies and they have different module efficiencies. Table 1.2 shows the PV module types and their module efficiency in the outdoor. PV module efficiency is most significant parameter and it affects the space requirements in the PV plant. To achieve an
output of one kilowatt peak in the crystalline solar modules, required surface area of the module is about 5 to 9 square meters and for thin-film modules, the surface area required for the same output is between 8 and 20 square meters.

**Table 1.2 Different PV Module’s efficiency in the outdoor**

<table>
<thead>
<tr>
<th>Type of PV module</th>
<th>Module efficiency</th>
<th>Surface area required for 1 kW&lt;sub&gt;P&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mono-crystalline silicon</td>
<td>13–19%</td>
<td>5–8 m&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
<tr>
<td>Poly-crystalline silicon</td>
<td>11–15%</td>
<td>7–9 m&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
<tr>
<td>Micro amorphous tandem cell (a-Si/µc-Si)</td>
<td>8–10%</td>
<td>10–12 m&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
<tr>
<td>Thin-film copper-indium/gallium-sulfur/diselenide (Cl/GS/Se)</td>
<td>10–12%</td>
<td>8–10 m&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
<tr>
<td>Thin-film cadmium telluride (CdTe)</td>
<td>9–11%</td>
<td>9–11 m&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
<tr>
<td>Amorphous silicon (a-Si)</td>
<td>5–8%</td>
<td>13–20 m&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

### 1.5 BASIC COMPONENTS OF PV SYSTEM

Photovoltaic modules and balance of system (BOS) components are combined together to form a PV system and is shown in Figure 1.11.
The BOS components comprise of DC to DC converter, energy storage device, charge controller, DC to AC converter and MPPT controller. The PV production cost is roughly divided into half between PV module cost and BOS components. The PV system’s efficiency is reduced by at least 50% due to inverter loss, battery loss, and system voltage drops.

1.6 TYPES OF PV SYSTEMS

Photovoltaic power systems are classified based on the functional, operational requirements and component configurations. The PV systems are classified as standalone PV systems and grid connected PV systems. Photovoltaic systems can be operated either in DC or AC output power mode depending on the system or load to which it is connected.

1.6.1 Standalone PV systems

Standalone PV system is not connected to the main electricity grid and it consists of PV modules, load, with or without batteries for energy storage and charge controller to control the battery charging and discharging. This system may be combined with the diesel generator and wind power generator and it can be operated with both DC and/or AC loads. When the PV modules are directly connected to the DC load, it is referred as direct coupled standalone PV system which is shown in Figure 1.12. It has no energy storage device and it needs maximum power point tracking controller to obtain the maximum power from the PV modules.

Figure 1.12 Direct-coupled Standalone PV system
During the night, the loads get uninterruptable power supply when the standalone PV system is connected with the energy storage device such as battery. The battery needs charge controller to control the battery power during charging or discharging conditions. Figure 1.13 shows a standalone PV system with energy storage device. An inverter is required when AC load is present in the system.

![Stand-alone PV system with battery storage and loads](image)

**Figure 1.13 Stand-alone PV system with battery storage and loads**

PV systems are used for residential applications, to supply power to off-grid residences and remote communities, and it may be combined with other renewable energy sources and diesel generators. PV and other on-site generation technologies are often less costly than grid extension when the distribution load is far away from the main grid. In developing countries, 1.4 billion peoples are inadequate to access power supply in villages.

### 1.6.2 Grid-connected PV System

Grid-connected PV system is shown in Figure 1.14 and it can be operated in parallel with the main electricity grid. The important components of the grid connected system are PV array, system monitor, inverter, utility breaker and utility meter. The function of inverter is to convert the PV module’s DC output into AC voltage and it provides the regulated voltage to
the main electricity grid. The power from the PV system to the utility grid is automatically stopped when the main grid is not energized. When the PV generated power is greater than the on-site load demand, the PV system supplies power to both on-site loads and to the main grid. During the night or cloudy days, the required power by the on-site loads is received from the main grid since the PV system’s output power is lesser than the connected electrical loads. The PV system does not need energy storage device when it is interconnected with the main grid. For safety measures, the grid connected PV system is not allowed to operate and fed the power to the main grid when the main grid is down for service or repair.

Grid-connected PV system applications are as follows:

The PV system connected to main grid is referred as grid connected PV systems and it does not require energy storage devices. The grid connected PV system can import power from the main grid when power shortage has occurred. It is disconnected from the main grid when fault occurs in the grid. Grid-connected PV systems are less expensive compared with power produced from the standalone PV systems. PV array having rating of few kilowatts to megawatts can be used in the grid-connected PV system. Cost of grid-connected PV system is much lower than standalone (off-grid) PV system since government provides subsidy for investors.

![Figure 1.14 Grid-connected PV system](image)
1.6.3 Hybrid PV Systems

The PV system is combined with the other power sources such as diesel generator and/or wind turbines and it is referred as a hybrid PV system. In order to enhance the performance of hybrid PV system, more sophisticated controls are required than the standalone PV system. Hybrid PV system is required to supply power to the remote areas and it consists of PV system, diesel generator and energy storage devices such as flywheel or super capacitor or battery.

The PV system reduce the running time of diesel generator and increase the lifetime of the generator. As a result, the diesel consumption is reduced. In PV/diesel systems, the diesel generator should start when energy storage device reach the certain discharge level and stopped again when energy storage device reach a sufficient state of charge. If the energy storage devices are charged more than sufficient charge, then it will reduce the life of the energy storage devices.

Hence, the hybrid PV systems need an automatic system for starting and stopping of the diesel generator and controlling its output. The configuration of hybrid PV system is shown in Figure 1.15.

Hybrid PV system applications are as follows:

Hybrid PV system is installed in remote location where main electricity grid connection does not exist and its application includes remote telecommunications sites, remote homes and villages, water pumping and boating. It may be located nearer to the distributed loads that lead to reduce the purchase and delivery of fuel to the site.
Advantages of photovoltaic systems are as follows:

- Solar power is free and abundant
- Solar energy provides clean and green energy
- PV module is environmentally friendly and reduce the emission of greenhouse gases
- PV modules have no moving parts and hence less maintenance cost is involved
- Onetime investment
- Reduces the import of fossil fuels and their usage
- Reduces global warming and makes reclamation of degraded land is possible
- The operating life of crystalline PV modules is 25 to 30 years and hence return on investment is possible
Disadvantages of photovoltaic systems are as follows:

- Initial cost of the PV systems is very high.
- Conversion efficiency is very low compared to other renewable energy systems.
- Efficiency of the crystalline silicon PV cell is high but its manufacturing cost is high.
- Efficiency of amorphous silicon thin-film PV cell is half of the efficiency of crystalline PV cell but it is less expensive to produce.
- PV plants require large area for installation.
- PV module’s intermittency and unpredictable power reduces the reliability.

Applications of photovoltaic systems are as follows:

- Cathodic protection System
- Solar powered water pumping
- Electric fences
- Rural electrification
- Remote lighting System
- Water treatment system

1.8 PV MODULE’S PARAMETERS

The single diode PV model of PV module is shown in Figure 1.16. In Figure 1.16, the term $I_{LG}$, $I_d$, $R_{se}$, $R_{sh}$, $I$ and $V$ represents light generated current, diode current, series resistance, shunt resistance, output current and output voltage respectively.
1.8.1 Light Generated Current ($I_{LG}$)

Figure 1.17 shows the $I$-$V$ curve of a PV cell in the fourth quadrant, when the PV cell is operating in its normal photovoltaic mode of operation. When the PV cell is forward biased at dark condition (i.e. no sunlight), its $I$-$V$ characteristics is shown as curve A in Figure 1.17. When sunlight is illuminated on the PV cell, electron hole pairs are generated depending upon the photons of the incident solar radiation. The collection of these generated charge carriers across the junction results in a net excess current from n-region to p-region. The magnitude of the light generated current is larger than the forward biased diode current. Therefore the $I$-$V$ curve A is moved down to curve B. The shift of the $I$-$V$ curve is proportional to the generation rate of excess electrons and holes. When the junction operates in fourth quadrant of the $I$-$V$ curve, power is delivered from the junction to the external load. The $I$-$V$ characteristics curve for a solar cell is present only in the fourth quadrant as shown in Figure 1.17, but this $I$-$V$ curve is shifted to the first quadrant for our convenience as depicted in Figure 1.18. $I$-$V$ characteristics of the PV cell shows that the PV cell has controlled voltage and controlled current. Hence, the PV cell is not damaged when it is operating in either open circuit or short circuit conditions. The Fill Factor (FF) is defined as the ratio of the maximum power from the real PV cell to the maximum power from an ideal PV cell.
According to the PV cell made by different PV technologies, fill factor varies from 0.5 to 0.82.

![Figure 1.17 I-V characteristics curve of PV cell at dark and illuminated condition](image)

**Figure 1.17**  *I-V* characteristics curve of PV cell at dark and illuminated condition

![Figure 1.18 Conventional I-V characteristics curve of PV cell at illuminated condition](image)

**Figure 1.18**  Conventional *I-V* characteristics curve of PV cell at illuminated condition

1.8.2  **Short Circuit Current (**$I_{sc}$**)**

The short circuit current in the PV module is due to the generation and collection of light generated carriers. For an ideal solar cell, the short circuit current is approximately equal to the light generated current. The short
circuit current is less than the light generated current when the value of series
resistance is high.

1.8.3 Open Circuit Voltage ($V_{oc}$)

The open circuit voltage of PV module mainly depends on the reverse saturation current and light generated current. The open circuit voltage increases with the bandgap increases as the recombination current fall. There is drop in $V_{oc}$ at very high bandgap due to the very low $I_{sc}$.

1.8.4 Effect of Irradiation

Solar irradiance is a measure of the irradiance produced by the Sun in the form of electromagnetic radiation, which is observed by humans as sunlight. Irradiance is the rate of energy that is being delivered to a surface area at any given time.

\[
\text{Irradiance} = \frac{\text{Power}}{\text{surface area}} \quad (1.1)
\]

Insolation is the total amount of solar radiation energy received on a given surface area during a given time. While the irradiance denotes the instantaneous rate at which power is delivered to a surface, the insolation denotes the cumulative sum of all the energy striking the surface for a specified time interval. This interval must be specified in order to make sense, and the typical unit of time measurement is the hour. The resultant insolation equation is as follows:

\[
\text{Insolation} = \frac{\text{Power} \times \text{Time}}{\text{surface area}} \quad (1.2)
\]

The average value of irradiated solar energy at the top of the earth’s surface is 1367 W/m$^2$. Approximately, the irradiated solar energy on the earth surface is 1000 W/m$^2$ and it is considered as the reference value for the PV module. The solar irradiation is measured by the instruments such as pyrheliometer and pyranometer. The PV module’s output power increases with the increase of irradiation. The output power increases with increasing
irradiation primarily due to increase in light generated current which has linear relation with irradiation. The output current of the PV module directly depends on the solar irradiation but the output voltage of the PV module does not directly depend on the solar irradiation.

The PV cell illumination intensity depends on the factors such as angle of incidence, wavelength, solar energy concentration, transmission losses in cover slides of PV module, optical losses and shadows.

1.8.5 Effect of Temperature

Temperature affects the $I-V$ characteristic equation of PV module in two ways due to the dependence of thermal voltage ($V_t$) and reverse saturation current ($I_{sat}$) on temperature. While increasing temperature reduces the magnitude of the exponent term in the PV characteristic equation, the value of reverse saturation current increases exponentially with temperature. As a result, the open circuit voltage reduces with increasing temperature. The open circuit voltage of a PV cell decreases by 2.3 mV/°C when the crystalline PV cell temperature increases. $V_{oc}$ decreases approximately by 0.5%/°C for most crystalline silicon PV cells but the short circuit current slightly increases with increase in the PV cell temperature. As a result, the output power of PV cell also decreases by approximately 0.5%/°C and for high efficient crystalline PV cell, the power is reduced by 0.35%/°C. In amorphous silicon PV cell, the open circuit voltage decreases by 0.20%/°C to 0.30%/°C when the temperature increases. The amount of light generated current ($I_{LG}$) increases slightly with increasing temperature due to the increase in the number of generated carriers. The light generated current increases by 0.065%/°C and 0.09%/°C for crystalline silicon cell and amorphous silicon cell respectively. When the temperature increases, the open circuit voltage is mostly affected compared to the short circuit current. The overall effect of temperature on cell efficiency
tends to be similar to that on open circuit voltage. Crystalline PV cell’s efficiency decreases by 0.50%/ºC and amorphous silicon cell’s efficiency decreases by 0.15%/ºC to 0.25%/ºC.

In figure 1.19, the effect of temperature on the $I$-$V$ characteristics curve of PV cell is analysed for various temperature conditions.

![Graph showing the effect of temperature on the $I$-$V$ characteristics curve of PV cell.](image)

**Figure 1.19  Effect of temperature on the $I$-$V$ characteristics curve of PV cell**

**1.8.6 Parasitic Resistance**

The parasitic resistance in the PV module comprises of series and shunt resistance. These resistances reduce the efficiency of the PV module by dissipating power when current flows.
1.8.6.1 Series resistance ($R_{se}$)

The series resistance is produced by the contact resistance between the metallic contacts and the semiconductor material, and the resistance of metallic contacts at the front and the rear of the PV cell. In a PV module, if mismatch occurs between the $I$-$V$ characteristics of the PV cells then it will increase the overall series resistance of the PV module. As series resistance increases in the PV module, fill factor decreases and the voltage difference between the junction voltage and the terminal voltage becomes more for the same current, which leads to slight reduction in the short circuit current. Large value of series resistance will produce significant reduction in the short circuit current (Jung & Ahmed 2012). The maximum power of PV module may be approximated as the maximum power in the absence of series resistance minus the power dissipated in the series resistance under that condition. Maximum power of the PV cell can be obtained approximately by the equation (1.5).

$$P_{mpp} \approx I_{mpp}V_{mpp} - I_{mpp}^2 R_{se}$$  \hspace{1cm} (1.5)

In Figure 1.20, the effect of series resistance on the $I$-$V$ characteristics curve for various series resistance values is shown.

![Figure 1.20 Effect of series resistance on the $I$-$V$ characteristics curve of PV cell](image-url)
1.8.6.2 Shunt resistance ($R_{sh}$)

The presence of shunt resistance in a PV module is due to poor design and manufacturing defects, which leads to increase the power loss significantly. Low value of shunt resistance produces more power loss in the PV cell and it provides alternate current path for the light generated current. This alternative path reduces the flow of current through the PV cell junction and also it reduces the voltage from the PV cell. Particularly, at low irradiation levels, the effect of shunt resistance is severe since there will be less light generated current. In addition, at lower voltages where the effective resistance of the PV cell is high, the impact of a resistance in parallel is large. As shunt resistance decreases, the PV module output current decreases significantly with small reduction in the open circuit voltage.

In Figure 1.21, the effect of shunt resistance on the $I-V$ characteristics curve of PV cell is shown for various resistance values.

![Figure 1.21 Effect of shunt resistance on the I-V characteristics curve of PV cell](image-url)
1.8.7 Reverse Saturation Current ($I_{sat}$)

When a p-n junction diode is reverse biased at very low temperature, a negligibly small current flows and it is independent of the applied voltage. This current is called as reverse saturation current and it has small effect in the $I$-$V$ characteristics curve.

Generally, in a p-n junction diode, it is assumed that there is no recombination loss in the depletion region but in a real PV cell, significant recombination loss occurs in the depletion region. The recombination current is generated due to the flow of majority carriers from n-region to p-region and it dominates at low voltage. Diffusion current is generated due to the diffusion of minority carriers in the n and p regions across the depletion region and it dominates at higher voltages. The diffusion current’s contribution is significant to the reverse saturation current of the PV module if the minority carrier concentration is large within the n and p region.

When the PV module’s temperature increases, minority carriers in the PV cells increase and hence the reverse saturation current increases rapidly. This also results in reduction in the bandgap. If the ideality factor of PV cell varies then the reverse saturation current also varies.

In a PV cell, if the reverse saturation current increases, then the value of open circuit voltage increases. Approximately, the value of reverse saturation current varies between $1 \times 10^{-3}$ A to $1 \times 10^{-12}$ A (Gow and Manning 1999). The effect of different reverse saturation current densities on the $I$-$V$ characteristics curve is shown in Figure 1.22.
1.8.8 Ideality Factor ($A$)

The ideality factor is a significant parameter in determining the PV cell’s $I-V$ characteristics.

Figure 1.22 Effect of reverse saturation current on the $I-V$ characteristics curve of PV cell

Figure 1.23 Effect of ideality factor on the $I-V$ characteristics curve of PV cell
In PV cell, the ideality factor mainly depends on the voltage across the cell. Under normal operating conditions, PV cell’s operation may be dominated by the recombination in the space charge region. The value of ideality factor is directly proportional to the temperature under both dark and light conditions. If the value of ideality factor decreases, then the open circuit voltage decreases. For most of the PV cells, the value of ideality factor range from 1 to 2. The effect of ideality factor value on the I-V characteristics curve is shown in Figure 1.23.

1.9 INTRODUCTION TO PV MODELLING

The photovoltaic module behaviour can be identified by using the PV model equivalent circuit. Modelling of PV module is important to study the operation of isolated loads and grid that uses PV generators. A mathematical modelling of PV module is required which is able to replicate the I-V characteristics under varying environmental conditions such as varying irradiation ($G$) and temperature ($T_c$). The grid or isolated load requires the power generated from PV plants to be maximized for which the PV systems are necessary to operate at its MPP and also the maximum power point tracking controllers need information about the PV module’s maximum power at MPP. Under varying environmental conditions, to accurately estimate the PV module’s output power, accurate determination of the parameters in the PV model is required. From various literatures, it is found that several researchers concentrated to develop accurate mathematical modelling of a PV module since the output power from the PV module is intermittent, nonlinear, and also varies with environmental conditions (Abdelsalam et al 2011). Mathematical modelling of PV module is also important for simulation studies. Extensive works have been carried out in the literature about the modelling of PV module.
The manufacturer’s datasheet of the PV module provides parameter value such as short circuit current ($I_{sc}$), open circuit voltage ($V_{oc}$) and maximum power point ($V_{mpp}$, $I_{mpp}$) at standard test condition (at $G=1000$ W/m$^2$ and $T_c=25°C$) and nominal operating cell condition (NOCT) (at $G=800$ W/m$^2$ and $T_c=47±2°C$). These values are very significant for PV module modelling. To exactly characterize the PV model, some of the parameters such as the light generated current, ideality factor, reverse saturation current, series resistance and shunt resistance are required. But, commonly the PV module manufacturers do not provide aforesaid parameters. The irradiance ($G_{stc}$), and the cell temperature ($T_{stc}$) value are given at standard test conditions (STC) which are $G=1000$ W/m$^2$ and $T_c=25°C$ respectively. Temperature coefficients of short circuit current ($k_i$), open circuit voltage ($k_v$) and maximum power ($k_p$) are also provided by PV module manufacturer’s data sheet.

1.10 IMPORTANCE OF THE RESEARCH

From the literature, it is found that several researchers tried to develop a perfect mathematical model for a PV module. The MPPT controller is essential to obtain the optimal power from the PV module under all operating conditions. In simulation, the power electronic converter used in the MPPT circuit needs an accurate simulation model of the PV module to achieve the maximum power point (MPP) under varying environmental conditions (Ishaque et al 2011a).

The PV module designers, PV module manufacturers, MPPT controller designers and PV researchers need reliable information on the performance of the PV systems. In particular, the high penetration of PV modules into a power system requires predicting the maximum power flow from the PV modules for analysing the future development of new grid, PV inverter control strategies, storage unit sizing, as well as investigations of the
economic and technological impacts on the whole energy system. Hence an accurate modelling of PV module is required for the PV system’s performance studies.

1.11 LITERATURE SURVEY

Several researchers developed various models for PV module such as single diode and two diode PV models. While deriving the above models some approximations and assumptions are made which leads to slight difference between the estimated parameters value and experimentally obtained parameters value. Numerical techniques are used to obtain the parameters of the PV model. The computation time taken to obtain the solution varies depending on the procedure that is used to solve the problem. To study the performance of PV modules in the islanded mode operation and when connected to the main electricity grid accurate modelling of PV module is important. Mathematical modelling of PV module is required which is able to predict the maximum power at MPP with reasonable accuracy under varying environmental conditions. The literature review has been classified into sub groups as follows:

1.11.1 Single Diode PV Model

The single diode PV model has been categorized into three parameter PV model, four parameter PV model and five parameter PV model.

Saloux et al (2011) proposed a method to eliminate the iterative calculations for parameter determination of the PV model. A simplified single diode three parameter PV model was used to investigate the characteristics of PV module. Simple analytic expressions for the PV model parameters such as light generated current, reverse saturation current and ideality factor were
proposed which reflect the deviations from the reference $I$-$V$ characteristics provided by the manufacturer’s datasheet.

Walker (2001) proposed a single diode four parameter $R_s$ model which consists of light generated current, reverse saturation current, ideality factor and series resistance. In his work, the series resistance was calculated numerically and shunt resistance was neglected. The ideality factor was considered as constant and its value was taken between 1 and 2.

Xiao et al (2004) proposed a single diode four parameter PV model to calculate the output power of the PV module under different irradiation and temperature conditions for different PV technologies such as mono-crystalline, poly-crystalline and thin-film technology.

Alonso-Garcia & Ruiz (2006) analysed the behaviour of a PV cell in reverse bias condition for single diode PV model. Under dark conditions, breakdown voltage and shunt resistance of the PV model parameter were evaluated and the effect of breakdown with temperature in a PV cell was investigated.

Celik & Acikgoz (2007) predicted the operating current of the single diode four and five parameter PV model. In a simplified four parameter PV model, the shunt resistance value is taken as infinite and it is neglected. Dongue et al (2012) proposed a four and five parameter PV model and these PV model parameters were evaluated by analytical method. The four parameter PV model shows less accuracy compared to the five parameter PV model. In a four parameter PV model, the simulated $I$-$V$ and $P$-$V$ characteristics curves of the PV module inadequately fit with the experimental characteristics curves since the shunt resistance effect was neglected.
Salih et al (2012) evaluated the performance of the single diode PV model in which the shunt resistance effect is neglected. The ideality factor ($A$) of the PV module varies between 1 and 2, where $A=1$ for an ideal diode and $A=2$ for a non-ideal diode. In the PV cell, defects are introduced either in manufacturing or due to heating of the PV panel by sunlight which causes more recombination loss and increases the ideality factor value from 1 to 2. Usually, in multi junction PV cells, the ideality factor value is higher than 2 and it has more number of p-n junctions. Multiple p-n junctions increase the value of ideality factor.

Phang et al (1984) developed a single diode PV model by extracting the parameters using the analytical method and it needed some assumptions in the derived expressions. These results are compared with the parameters extracted using the Newton Raphson (NR) method. Numerical methods need proper initial value for the parameters and it takes more time for convergence if proper initial values are not provided.

King et al (2004) proposed a method to extract the unknown parameters of a single diode five parameter PV model accurately but this model was more complex because it required more number of input data to characterize the PV model. Normally, these data are not available in the manufacturer’s data sheet.

Badescu (2006) proposed a constrained optimization method to find the electrical output power of the series-parallel PV module. The PV module efficiency is increased with the colder climates and higher latitudes and it strongly depends on the geographical location. The influences of climate and latitude are significant in finding the output power of the PV module.
Cotfas et al (2008) reviewed some of the methods to determine series and shunt resistances and presented a new method to determine series and shunt resistances and compared the results to previous literature methods. The new method is based on the single diode model for PV cell and the dependence of the series resistance on the irradiance levels was also presented. A complex programme using LabVIEW was developed to determine the cell characterization and implicitly for the determination of series resistance.

Villalva et al (2009) proposed a different approach to find the value of series resistance and shunt resistance of the single diode five parameter PV model. The PV module series resistance value was slowly increased and the corresponding value of shunt resistance was found through iterative process, until experimental power from manufacturer’s datasheet matches with the simulated power at MPP. If there is a mismatch in the incremented value of series resistance against the specified value of series resistance, the value of PV model parameters’ error exceeds the threshold value. In this PV model, the author also proposed a modified equation for reverse saturation current. The drawback of this model is that the value of ideality factor is assumed as unity, but ideality factor value varies according to the environmental conditions. The temperature dependence of the diode reverse saturation current was proposed and used in the model. The reverse saturation current and light generated current values were calculated separately not along with the other parameters such as ideality factor, shunt resistance and series resistance. Furthermore, the author considered the expression for reverse saturation current derived from single diode four parameter I-V characteristic equation and it reduces the accuracy of the model. Maximum power of the PV module was evaluated by using Newton Raphson (NR) method under varying environmental conditions.

Kishor et al (2010) identified the parameters of the single diode PV model by considering the environmental factors such as the effect of
irradiation, temperature, dust, shadows and wind velocity. If dust particle is deposited in a PV module, the open circuit voltage remains unchanged but output current decreases significantly. Thus, the effect of dust particle reduces the efficiency of the PV module. The wind velocity does not affect the PV output power significantly when it varies between 7 to 18 m/sec. The effect of dust particle and shadows causes increase in the series resistance value of the PV module.

Carrero et al (2011) used the Newton Raphson (NR) method to calculate the parameters of the PV model at standard test conditions by finding the initial value of few PV model parameters analytically. A system of three implicit equations were derived from the derivatives of the $I-V$ curve at short circuit point, open circuit point and maximum power point by Sera et al (2007) to identify the three unknown parameters of the PV model using NR method and Bisection method.

Chatterjee et al (2011) used the guass seidel (G-S) method to estimate the parameters of the PV module. The successive under relaxation (SUR) method is used to estimate the MPP when the G-S method fails to converge. The initial values of parameters were calculated by trial and error method and it took more time to find the initial value of the parameters. Under varying environmental conditions, the author introduced expressions for ideality factor and series resistance at MPP. The author considered the value of shunt resistance as constant and it is calculated at STC. But in practice, the shunt resistance value will be varying according to the environmental conditions. This will reduce the PV module’s performance significantly.

Zhu et al (2011) derived a systematic method to extract the five-parameter model of the PV module using the data available from the manufacturer. The author determined the ranges of PV module parameters
such as ideality factor, series resistance and shunt resistance, and the sensitivity of the parameters are analysed using suitable expressions. These expressions are also used to select the initial value of aforesaid parameters. This procedure ascertains the stability and increases the convergence speed of solving non-linear equation. Even though, this model provided accurate result, if proper value of ideality factor is not assigned then it may lead to high computational error. Parameter estimation in this model is difficult due to more number of derivative functions involved.

Ghani & Duke (2011) obtained exact solution to PV model by using Lambert W-function. However, numerical method is used to evaluate the Lambert W-function. The accuracy is found to be good using this function with the cost of operating speed. The PV module operates at different operating conditions but the manufacturers do not provide sufficient information about the PV module under various operating conditions to evaluate its overall performance.

Several researchers (Lo Brano & Ciulla 2013; Kulaksiz 2013 and Ishaque & Salam 2011) concentrated on the single diode five parameter PV model due to its simple calculation procedure. This model does not account for the recombination loss in the depletion region. Ly Diallo et al (2012) found the value of shunt resistance and series resistance as a function of junction surface recombination velocity.

Kulaksiz (2013) proposed a single diode PV model and the PV model parameters such as series resistance, shunt resistance, and ideality factor were evaluated accurately by using the adaptive neuro-fuzzy inference system (ANFIS). This model required large number of training data to find the value of unknown parameters of the PV model and thereby the PV module characteristics. It was also a time consuming method.
Many methods have been proposed to obtain the value of ideality factor and its value varies with the operating conditions for the same PV module. When the PV module’s temperature increases, the value of ideality factor (A) decreases under both dark and illuminated conditions, but the ideality factor’s value increases with the increasing irradiation condition (Bashahu & Nkundabakura 2007). The temperature value of the PV module is taken as the average of the front and rear face’s temperature of the PV module. Bashasu & Nkundabakura (2007) observed the ideality factor value to be higher than 2 but its value has been observed to be lower than 1 by Carrero et al (2011).

Ciulla et al (2014) analysed five most recent PV models based on the parameters determination, physical assumptions, approximation in the mathematical expressions and algorithm used for solving the PV model in detail. The PV models developed by de Blas et al (2002), Hadj Arab et al (2004), de Soto et al (2006) and Lo Brano et al (2010) require reciprocal of the slopes of the $I-V$ characteristics curve of the PV module at the open circuit voltage and short circuit current to find the initial value of series and shunt resistance respectively. These values are used in the numerical algorithm. Generally, the manufacturer’s datasheet does not provide these data and graphical evaluation should be carried out. If the datasheet provides a graphical representation of $I-V$ characteristics curve, then the graphical evaluation is possible. However, the graphical evaluation is based on approximation which may produce error in the determination of parameters. Hence, it can affect the performance of the PV module. Under varying temperature conditions, the de Blas model does not allow calculation from the $I-V$ characteristics curve. The Hadj Arab et al (2004) made several simplifications in the PV model that affects the performance of the model. De Soto et al (2006) proposed a single diode PV model and the parameters were
calculated through the nonlinear solver. This solver may have some difficulties while solving the system of equations.

### 1.11.2 Two Diode PV Model

Several researchers concentrated on the two diode PV model since this PV model gives accurate results while calculating maximum power at MPP under varying environmental conditions.

Enebish et al (1993) proposed two diode PV model to extract the parameters value and maximum power of the PV module and assumed the value of ideality factor of diffusion diode and recombination diode. Diffusion loss and recombination loss is considered in a two diode PV model.

Negative output voltage is generated in a non-uniformly illuminated PV module, particularly during partial shading of the PV module. If there is no bypass diode across the PV module, diode breakdown may occur during negative voltage region (Quaschning & Hanitsch 1996). Generally, in a two diode PV model, diode breakdown is not taken into account and the developed PV model includes extension term that describes the diode breakdown at high negative voltages. In the negative voltage region, convergence speed is very low or may diverge while finding the initial value of parameters by using NR method. In this paper, the parameter extraction was done by applying NR method and it requires proper initial value to speed up the algorithm. Here bisection method was used to calculate the initial value of the parameters for the NR method. A mesh circuit was formed to generate the required equations which made the system more complex and more computational time was taken to find the parameters of the PV model.

Gow & Manning (1999) proposed an accurate two diode PV model and it was solved by using the well-known iterative technique such as Newton Raphson method. Their PV model equation contains thirteen constant values.
and two equations used in the model are exponential in nature and implicit. Hence, this model was somewhat complex and it takes more computational time to solve. In this model, the I-V characteristic equation needs to find seven unknown parameters.

Chao et al (2008) carried out the PV module simulations with the use of neural networks, fuzzy and neuro-fuzzy algorithms for improving the performance of the PV module. These algorithms are used to achieve the accurate modelling of PV module but the application of above algorithms is much difficult when the PV system is expanded in its rating.

Sandrolini et al (2010) simulated the I-V characteristics curve of a PV module that was fitted with the experimental I-V characteristics curve of the same module by using the particle swarm optimization algorithm with cluster analysis. The photovoltaic generator interfacing to the grid requires efficient power electronic converter. For extracting maximum output power from the PV module under all operating conditions, the power electronic converter should be designed with a maximum power point tracking controller. Proper design of MPPT controller needs the knowledge of maximum power of the PV module at MPP under different irradiation and temperature conditions. Hence, modelling of the PV module is important.

Ishaque et al (2011b) proposed the two diode PV model to reduce the complexity and a comparative study of parameter estimation for single diode PV model and two diode PV model was presented for validation. They derived the expression for reverse saturation current from the I-V characteristics equation of single diode four parameter PV model.
1.11.3 Maximum Power Point Tracking (MPPT) Controller

Abdel Salam et al (2011) proposed the adaptive perturb and observe technique to track the MPP at different operating conditions and it was used to ensure the maximum use of the available solar energy. For proper design of MPPT controller, it needs accurate simulation model to predict the maximum power point of PV module at all operating conditions. PV based microgrid should be reliable when it is connected to the main grid and it has to forecast the maximum power from the PV module to identify the power flow from the microgrid to the main grid.

Esram & Chapman (2007) surveyed nineteen different techniques for MPPT controller which was used to find the maximum voltage or maximum current of the PV module at which a PV module has to operate to obtain the maximum power for a particular operating condition. Dave Freeman (2010) analysed seven different MPPT techniques to evaluate the maximum power at MPP. The value of maximum current, maximum voltage at MPP has linear relationship with the short circuit current and open circuit voltage respectively under varying irradiation and temperature conditions as given by equations (1.6) and (1.7).

\[ I_{mpp} = k_1 I_{sc} \]  \hspace{1cm} (1.6)
\[ V_{mpp} = k_2 V_{oc} \]  \hspace{1cm} (1.7)

where \( k_1 \) and \( k_2 \) are the proportional constant.

The constant \( k_1 \) varies between 0.9 to 0.98 and constant \( k_2 \) varies between 0.7 to 0.8.

1.12 RESEARCH GAP IDENTIFIED FROM LITERATURE SURVEY

From the literature survey, it is found that all the numerical methods used in PV modelling need proper initialization of parameters value
for getting fast convergence speed. Several researchers have proposed expressions for finding the initial value of the parameters in the single diode PV model which involves more complex calculation procedure and some of the researchers calculate the initial value of the parameters by trial and error method. In this research work, new expressions are introduced for initialization of some of the parameters in the single diode PV model to avoid the complexity.

For obtaining the value of the reverse saturation current in the two diode PV model, several researchers have used the single diode PV model $I-V$ characteristics equation which gives fairly accurate result. In this research work, the reverse saturation current in the two diode PV model has been found using the two diode PV model $I-V$ characteristics equation itself. This results in improved accuracy in finding the reverse saturation current.

Most of the researchers assumed that the shunt resistance value in the single diode PV model remains constant which is calculated at STC but actually the value of shunt resistance will change when the irradiation and temperature varies. In this research work, a new equation is developed to find the shunt resistance value at any irradiation and temperature.

1.13 OBJECTIVES OF THE RESEARCH

- To develop new expressions to identify the parameters of single diode PV model and two diode PV model, and to estimate the maximum power of the PV module under varying environmental conditions.
- To implement different numerical techniques such as NR method, G-S method and SUR method for finding the value of parameters in
the PV model and maximum power of the PV module under varying environmental conditions.

- To introduce new expressions to find the initial value of shunt and series resistances of the PV model that can be used in the numerical techniques for finding the value of parameters in the PV model.
- To estimate the performance of the different PV modules made by different PV technologies under varying environmental conditions by doing simulation using MATLAB with the single diode and two diode PV model and to verify the results with the experimental data.

1.14 ORGANIZATION OF THE DISSERTATION

This dissertation has been organized as seven chapters and the details are given below.

In chapter 2, a single diode PV model has been investigated. The numerical methods such as G-S and SUR are used to estimate the parameters of the PV module made by different photovoltaic technologies such as mono-crystalline, poly-crystalline and thin-film under varying irradiation and temperature conditions. New equations are derived based on $I-V$ characteristic equation of the PV module for finding the maximum voltage and maximum current at maximum power point under varying irradiation and temperature conditions.

In chapter 3, single diode PV model parameters are extracted at various operating conditions by numerical methods and two new equations are introduced to initialize the value of the series and shunt resistances in order to obtain good convergence speed in numerical methods. In addition, two new equations are proposed to find the ideality factor and shunt resistance under varying environmental conditions and to obtain accurate MPP of the PV
model under those conditions. Experimental verifications show good estimation accuracy for different PV modules with the simulated results of the proposed PV model.

In chapter 4, simplified six parameter two diode PV model has been proposed to extract the parameters of the PV module and estimate the maximum power at maximum power point at all operating conditions. A new equation is proposed to find the reverse saturation current more accurately based on the six parameter PV module characteristic equation. The results are verified by finding the PV model of six different PV modules belonging to different PV technologies such as mono-crystalline, poly-crystalline and thin-film using MATLAB simulation and comparing the simulated results with the experimental data given in the literature.

In chapter 5, an improved seven parameter two diode PV model has been developed for accurate estimation of PV module parameters at standard test condition (STC). To reduce the complexity of calculation, the parameters to be determined are reduced to four and the values of three parameters are assumed as constant. A new equation is proposed to accurately estimate the value of reverse saturation current of the PV module. Five different PV modules belonging to different PV technologies are investigated for accurate estimation of PV module’s maximum power at maximum power point for a wide range of changing environmental conditions.

In chapter 6, comparative analysis is made between the proposed PV models in this research work for the same PV module. For each PV model, limitations and advantages are discussed.

In chapter 7, conclusion of the thesis is presented, and contribution of the research work and future scope are also discussed.